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The Effect of Adaptation Measures on the Adoption of Clean Technologies

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Abstract

Climate change is one of the greatest challenges facing our planet in the foreseeable future and despite the urgency of the situation global GHG emissions are still increasing. In this context, and since future climate changes appear now unavoidable to some extent, adaptation measures have recently gained a new political momentum as an important component of climate policies. Contrary to mitigation options, adaptation measures do not reduce emission levels but reduce their impacts. To assess the relationship and effects on the global economy of both mitigation and adaptation, we use in this paper an integrated assessment model (IAM) that includes both adaptation strategies and access to clean technologies for mitigation. We find that the relationship between adaptation and mitigation is complex and largely dependent on their respective attributes, with weakly effective adaptation acting as a late complement to mitigation efforts. As its effectiveness increases, adaptation becomes a substitute for mitigation. Sensitivity analysis on the discount rate also indicates that choosing a rate is certainly not innocuous on the policy recommendations with higher rate values postponing both mitigation and adaptation efforts.

Key Words: Adaptation, Climate change, Mitigation, Clean technology, Integrated assessment.

Résumé

Les changements climatiques sont l'un des plus grands défis auxquels notre planète doit faire face dans l'avenir, mais, en dépit de l'urgence de la situation, les émissions mondiales de GES augmentent toujours. Dans ce contexte, et puisque de futurs changements climatiques semblent maintenant inévitables, les mesures dites d'adaptation se sont récemment imposées comme une composante importante des politiques climatiques. Contrairement aux mesures d'atténuations, les mesures d'adaptation ne réduisent pas les niveaux d'émission mais leurs impacts. Pour évaluer les effets sur l'économie mondiale des mesures d'atténuation et d'adaptation, nous employons dans ce papier un modèle dit d'évaluation intégrée qui inclut ces deux types de stratégie. Nous constatons que les rapports entre l'adaptation et l'atténuation sont complexes et dépendent en grande partie de leurs attributs respectifs, avec une adaptation faiblement efficace agissant seulement en tant que complément tardif des efforts d'atténuation. Mais à mesure que son efficacité augmente, l'adaptation se substitut à l'atténuation. Une analyse de sensibilité sur le taux d'escompte indique également que le choix de ce dernier n'est certainement pas sans conséquence sur les recommandations politiques dans la mesure où l'emploi d'un taux plus élevé repousse dans le temps les efforts d'atténuation et d'adaptation.

1 Introduction

Climate change is one of the greatest challenges facing our planet in the foreseeable future. It is expected, according to the Intergovernmental Panel on Climate Change (IPCC, 2007), to impact ecosystems and the environmental services they provide (in terms of food and water in particular) but also human societies (affecting human health and regional economies, for instance). Besides, the IPCC argues that human activities, through the greenhouse gases (GHG) they release in the atmosphere, are responsible for most of the observed increase in global average temperatures up to now, and that they shall continue to do so in the absence of ambitious climate policies to reduce GHG emissions.

Despite the urgency of the situation, global GHG emissions are still increasing, in particular because there is not yet an overall agreement to curb world emissions. In this context, and since future climate changes appear now unavoidable to some extent, adaptation measures have recently gained a new political momentum as an important component of climate polices. Contrary to mitigation options, adaptation measures do not reduce emission levels, but provide strategies to deal effectively with climate change effects by reducing their impacts (Tol, 2005; Adger et al., 2007; Klein et al., 2007b). Adaptation strategies cover a large array of sectors and options, from new agricultural crops, modified urban planning (dikes, sewerage systems), medical preventions against pandemic to controlled migrations of population and activity changes. Depending on the degree of anticipation (and requirement for it), adaptation measures can be reactive or preventive: vaccination campaigns can be made mandatory without any materialized threat (as precautionary principle) or could be offered only in case of pandemic urgency, for instance.

Compared to mitigation strategies, adaptation measures have two main strengths. First, their benefits are often immediate or very short-term, which reduces their exposure to uncertainty and discounting preferences. This immediacy is also beneficial for populations already vulnerable to certain impacts of climate change (Parry et al., 2009). Second, adaptation measures in effect privatize policies against climate changes by largely limiting the benefits of adaptation to those having invested in it. Adaptation avoids the free-riding problem traditionally associated with mitigation[1] and does not require concerted and simultaneous actions, fostering the advancement of regional or local projects. As pointed by Olson (1965), "*only a separate and 'selective' incentive will stimulate a rational individual in a latent group to act in a group-oriented way*" and to that goal, adaptation is effective.

Both international institutions and governments have recognized these strengths and have now started to conceive and finance portfolios of adaptation projects. For instance, the World Bank has initiated a US$500 million Pilot Program for Climate Resilience and prepared in 2009 a new study to assess adaptation costs, areas and applicability in developing countries (Margulis and Narain, 2009). Under the United Nations Framework Convention on Climate Change (UNFCCC), a new adaptation fund has also been launched, financed with 2% of the shares of proceeds coming from the issuances of certified emission reduction units (CERs) under the clean development mechanism (CDM). During the recent Copenhagen conference (COP15), it was also decided to create the Copenhagen Green Climate Fund (CGCF), with a first budget of US$30 billion in the 2010-2012 period to invest in mitigation and adaptation projects. This fund should eventually reach US$100 billion by 2020.[2] In addition to those dedicated projects, adaptation strategies are now more and more blended into more traditional development projects and official development assistances (ODA) (Klein et al., 2007a). They are also pushed forward in developed countries albeit without the kind of targeted recognition used for developing countries.

Considering the simultaneous promotion of adaptation strategies and the relative weaknesses of mitigation policies so far, the question of their respective role should be assessed, both for policy and investment purposes. It could be that adaptation strategies become inexpensive alternatives to mitigation approaches, at least as long as no clear international agreement forces the world's economies to transition into an more efficient

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[1] A country say may hesitate to pay for emission reductions that will also impact favorably those who did not participate in any mitigating efforts, thus unbalancing its competitiveness (Olson, 1965; Baumol and Oates, 1988).

[2] Copenhagen Accord, Conference of the Parties (COP-15), December 2009, articles 8 and 11 (http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf).

economy (in terms of GHG emissions). If this is the case, what would be the impact on the transition timing towards such an economy? More importantly, what could be the long run effects, both in terms of GHG concentrations, overall costs and damages and growth trajectories?

To answer these questions, one may use an integrated assessment, an interdisciplinary approach that uses information from different fields of knowledge, in particular socio-economy and climatology. Integrated assessment models (IAMs) are tools for conducting an integrated assessment, as they typically combine key elements of the economic and biophysical systems, elements that underlie the anthropogenic global climate change phenomenon. Examples of IAMs are DICE (Nordhaus, 1994, 2007), MERGE (Manne et al., 1995; Manne and Richels, 2005), RICE (Nordhaus and Yang, 1996) and TIAM (Loulou and Labriet, 2008; Loulou, 2008).

Research incorporating adaptation measures into integrated assessment models has been rare until recently, despite the importance of these models for current policy decisions. Hope et al. (1993) (updated in Hope, 2006) were the first to integrate adaptation as a policy variable in an IAM, the PAGE model. Bosello (2008) uses a FEEM-RICE model with mitigation, adaptation and R&D development in a strategic setting. de Bruin et al. (2009b) have proposed to include adaptation as an explicit strategy in the DICE model (AD-DICE). In follow-up studies, de Bruin et al. (2009a) expand this methodology to the RICE model (AD-RICE), Felgenhauer and de Bruin (2009) introduce uncertainty in the climate outcome and finally Hof et al. (2009) test for the effectiveness of the 2% levy proposed to finance the UNFCCC adaptation fund in a combined AD-RICE/FAIR model.

We use in this paper the deterministic version of a simple integrated assessment model (Bahn et al., 2008, 2010, thereafter referred to as BaHaMa) enriched to consider explicitly adaptation options. BaHaMa is in the spirit of the DICE model but distinguishes between two types of economy: the “carbon economy” (our present economy) where a high level of fossil fuels is necessary to obtain output and a so-called “carbon-free” or “clean economy” (an hydrogen economy, for instance) that relies much less on fossil fuels to produce the economic good. Besides, compared to AD-DICE, our approach provides some important distinctions. We do not consider adaptation efforts as costs (“*flow*”) but as investments (“*stock*”) and as such we emphasize on its proactive component in lieu of its reactive element (see Lecocq and Shalizi, 2007). We can therefore assess the timing of adoption of clean technologies in the presence of adaptation strategies and evaluate the sensitivity of their interactions to specific parameters. This element could be of importance in the current debate about the required incentives to foster adequate “green” R&D investments. Moreover, our model, while being close in certain aspects to the DICE model for comparison purposes, remains largely autonomous in its calibration procedure, allowing us to test a variety of parameter’s specifications.

The paper is structured as follows. Section 2 details our IAM with explicit adaptation options, thereafter referred to as Ada-BaHaMa. The section covers also some of the economic rationales behind the modeling choices. Sections 3 and 4 give the model’s results and additional sensitivity analyzes for the adaptation effectiveness and the discount rate. Finally we conclude in Section 5 and propose some further improvements and additional directions for research.

2 BaHaMa with explicit adaptation

2.1 Model description

An overview of Ada-BaHaMa is given in Fig. 1.

We next describe the different component of the original BaHaMa model and its new adaptation feature.

2.1.1 Production dynamics

Production (Y) occurs in the two types of economy (the carbon economy, referred to by an index 1, and the clean economy, referred to by an index 2) according to an extended Cobb-Douglas production function in

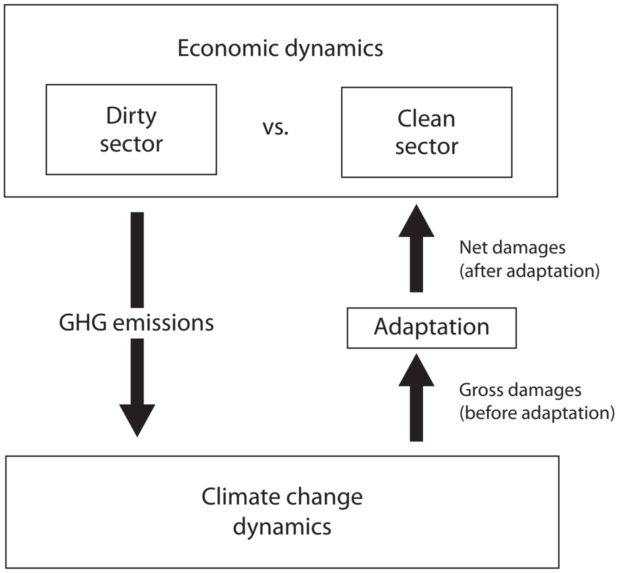

Figure 1: Schematic overview of Ada-BaMaMa.

three inputs, capital (K), labor (L) and energy (measured through GHG emission level E):

$$\begin{aligned} Y(t) = {} & A_1(t)K_1(t)^{\alpha_1}(\phi_1(t)E_1(t))^{\theta_1(t)}L_1(t)^{1-\alpha_1-\theta_1(t)} \\ & + A_2(t)K_2(t)^{\alpha_2}(\phi_2(t)E_2(t))^{\theta_2(t)}L_2(t)^{1-\alpha_2-\theta_2(t)}\,, \end{aligned} \tag{1}$$

where for each economy i ($i = 1, 2$): A_i is the total factor productivity, α_i the elasticity of output with respect to capital K_i, ϕ_i the energy efficiency and θ_i the elasticity of output with respect to emissions. Notice that capital stock in each economy evolves according to the choice of investment (I_i) and a depreciation rate δ_{K_i} through a standard relationship:

$$K_i(t+1) = I_i(t) + (1-\delta_{K_i})K_i(t) \quad i = 1, 2. \tag{2}$$

Besides, total labor (L) is divided between labor allocated to the carbon economy (L_1) and labor allocated to the carbon-free economy (L_2):

$$L(t) = L_1(t) + L_2(t). \tag{3}$$

2.1.2 GHG concentration dynamics

Let $M(t)$ denote atmospheric concentration of GHG at time t, in GtC equivalent. The accumulation of GHG in the atmosphere is described by the following equation:

$$M(t+1) = \beta(E_1(t) + E_2(t)) + M(t)(1-\delta_M) + \delta_M M_p, \tag{4}$$

where β is the marginal atmospheric retention rate, δ_M the natural atmospheric elimination rate and M_p the preindustrial level of atmospheric concentration. Notice that Eq. (4) is a very simple representation of the GHG concentration dynamics yet consistent with the archetypal DICE model. Besides, as in the original BaHaMa model, we choose here for simplicity not to compute temperature changes. On the one hand, this enables to compare with results reported for BaHaMa (Bahn et al., 2008, 2010). On the other hand, this would make tractable, in a future research, the extensive computations require to solve (as for the BaHaMa model) a stochastic control version of Ada-BaHaMa that would provide a sophisticated treatment of uncertainty (compared for instance to a standard stochastic programming approach).

2.1.3 Damage and adaptation frameworks

To model climate change damages and their economic impacts, we follow an approach used in the MERGE model (Manne and Richels, 2005). We compute in particular an economic loss factor (ELF) due to climate changes at time t, which is adapted to take into account the effects of adaptation $\mathrm{AD}(t)$:

$$\mathrm{ELF}(t) = 1 - \mathrm{AD}(t)\left(\frac{M(t) - M_d}{cat_M - M_d}\right)^2, \tag{5}$$

where M_d is the concentration level at which damages start to occur and cat_M the climate sensitivity dependent "catastrophic" concentration level at which the entire production would be wiped out. For the illustrative purposes of this paper and to have a comparable basis with the current literature on IAM with adaptation, M_d and cat_M are calibrated in order to replicate the damage intensity of DICE; see Section 2.2. Notice further that this loss factor applies on production levels, see Section 2.1.4, such that damages are computed as: $\mathrm{AD}(t)Y(t)\left(\frac{M(t)-M_d}{cat_M-M_d}\right)^2$.

In our model, adaptation reduces the damaging effects of GHG concentration and for simplification purposes it has neither impact on the total factor productivity (no innovation breakthrough is coming from adaptation investment) nor direct correlation with GHG emissions (as in the often cited air conditioned example). Contrary to the recent efforts by de Bruin et al. (2009b,a), we consider adaptation as an investment (stock) and not as a cost (flow), since for a large part adaptation projects will be directed towards infrastructure and medium-to-long-term economic transformations. To use the words of Lecocq and Shalizi (2007), we favor the proactive type of adaptation over the reactive one. This approach gives us greater flexibility over the nature of adaptation policies. By controlling for capital depreciation rate in the model, we can test for proactive effectiveness: if adaptation investments are in line with realized impacts, depreciations should be slow. On the contrary, inadequate strategies or incapacity to predict future damages will force to reinvest frequently, imposing a high deprecation rate on the adaptation capital. At the margin, with an annual depreciation of 100%, the adaption investment corresponds to a cost.

The adaptation dynamics is as follows:

$$\mathrm{AD}(t) = 1 - \alpha_{\mathrm{AD}}\frac{K_3(t)}{K_{3\max}(t)} \tag{6}$$

with α_{AD} representing the maximal adaptation effectiveness, $K_3(t)$ the amount of adaptation capital in period t and $K_{3\max}(t)$ the maximal amount of adaptation capital to be invested in each period to ensure the optimal effectiveness of adaptation strategies.

In our framework, adaptation costs should increase whenever atmospheric GHG concentration (and therefore damages) increases. To take this into account, we model $K_{3\max}(t)$ as an increasing function of the current GHG concentration:

$$K_{3\max}(t) = \beta_{\mathrm{AD}}\left(\frac{M(t)}{M_d}\right)^{\gamma_{\mathrm{AD}}}, \tag{7}$$

where β_{AD} and γ_{AD} are calibration parameters. The behavior of this function is determined by the calibration process. Nonetheless, we force the calibration to be bounded such that $\beta_{\mathrm{AD}} \geq 0$ and $\gamma_{\mathrm{AD}} \geq 1$. Hence, getting the full offsetting potential of adaptation will require more and more investment if mitigation is not also considered jointly.

2.1.4 Welfare maximization

A social planner is assumed to maximize social welfare given by the integral over the model horizon (T) of a discounted utility from per capita consumption $c(t) = C(t)/L(t)$. Pure time preference discount rate is noted ρ and the welfare criterion is then given by:

$$W = \int_0^T e^{-\rho t} L(t) \log[c(t)]\, dt. \tag{8}$$

Consumption comes from an optimized share of production, the remaining being used to invest in the production capital (dirty and/or clean), in the adaptation capital and to pay for energy costs. The presence of damages (defined by the ELF factor) reduces the available production such that:

$$\mathrm{ELF}(t)Y(t) = C(t) + I_1(t) + I_2(t) + I_3(t) + p_{E_1}(t)\phi_1(t)E_1(t) + p_{E_2}(t)\phi_2(t)E_2(t), \tag{9}$$

where I_3 is the investment in the adaptation capital and p_{E_i} are energy prices. Note also that adaptation stock evolves according to a relation similar to Eq. (2):

$$K_3(t+1) = I_3(t) + (1 - \delta_{K_3})K_3(t), \tag{10}$$

where δ_{K_3} is a depreciation rate.

2.2 Model calibration

The different modules of Ada-BaHaMa (adaptation, economy and climate) are basically calibrated on the models DICE (version 2007,[3] thereafter referred to as DICE2007) and AD-DICE (de Bruin et al., 2009b).

We start our calibration procedure by the adaptation component which is new the feature in the Ada-BaHaMa model. First, we calibrate ex-ante parameters defining the maximal amount of efficient adaptation capital ($K_{3\max}$). We use for this the most recent report that the World Bank (Margulis and Narain, 2009) issued on the cost of adaptation in developing countries for the period 2005-2055: to fully offset climate change impacts in developing countries, US$ 100 billion should be spent each year until 2055. Despite representing only a small share of the global economy, these adaptation costs, when adjusted for our model, still correspond to high values compared to the AD-DICE estimates. Second, the maximal adaptation effectiveness (parameter α_{AD}) is set to 0.33 (at most 33% of damages are avoided)[4] following results reported with AD-DICE. Third, to reproduce the magnitude of climate change damages estimated by DICE and AD-DICE, we use values of GHG concentrations, temperatures, gross damages and production from these models in order to calibrate parameters of our damage function (ELF). Damage estimates are presented in Fig. 2. Our calibration is slightly more conservative on damage than de Bruin et al. (2009b) but differences appear only for large increase in concentration. Besides, concentrations reached in Ada-BaHaMa never exceed 1140 GtC when mitigation options (clean technologies) are available; see Section 3.2.

The other modules of Ada-BaHaMa (economy and climate) are again basically calibrated on DICE2007. In particular, parameters in Eqs. (1), (2) and (4) are mostly from DICE2007. Note however that, compared to the dirty economy, production in the clean economy has a better energy efficiency but higher energy costs. The resulting overall production in Ada-BaHaMa reproduces then the economic output of DICE2007; cf. Fig. 3.

However, compared to DICE2007, the modeling of two types of economies implies an optimal trajectory, conditioned by a transition to the clean economy after 2070 to reduce climate change damages, that involves much less GHG emissions over the long run; cf. Fig. 4.

3 Results

In this section, we report on four different scenarios: a counterfactual baseline without any climate change related damages, an adaptation-only scenario where the clean technology is not available, a mitigation-only scenario where adaptation is not possible and finally a combined scenario with both mitigation and adaptation efforts. More precisely, we first detail impacts of these scenarios on dirty and clean production capital stocks as well as on adaptation capital stocks. We then look at effects on atmospheric GHG concentration and the corresponding climate change damages. Finally, we detail the overall effects on economic output.

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[3] See: http://www.econ.yale.edu/ nordhaus/DICE2007.htm.

[4] However and considering its importance in the determination of the optimal mix of strategies, we conduct in Section 4 sensitivity analyses for different–lower and higher–values of α_{AD}.

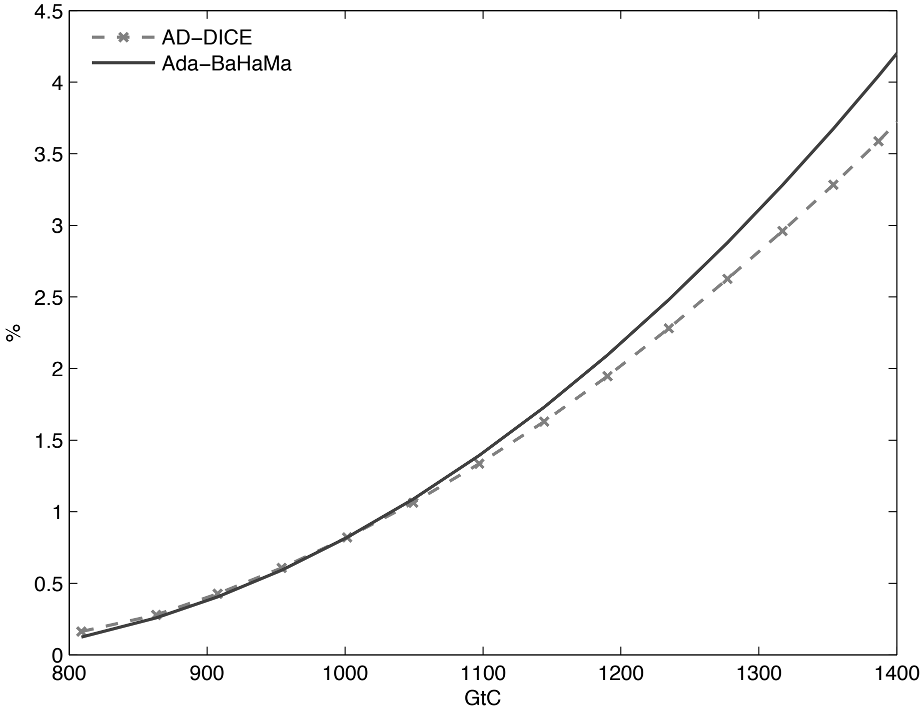

Figure 2: Damage levels (in percentage of production) for different atmospheric GHG concentration levels in Ada-BaHaMa and AD-DICE.

3.1 Capital accumulation paths

When comparing our scenarios, two important components stand out in the strategies deployed to address climate change: first, the existence and timing of a transition between the dirty and the clean economy (mitigation strategy), see Fig. 5 and 6, and second, the importance awarded to adaptation, especially when the clean technology is not available, see Fig. 7.

When the clean technology is not available (adaptation-only scenario), clean capital does not of course accumulate. The only mitigation effort corresponds then to a small reduction in dirty production. Consequently, accumulation of dirty capital is slightly reduced compared to the baseline. Conversely, when the clean technology is available (mitigation-only and combined scenarios), there is a clear transition between the two economies: the dirty capital is rapidly phased out after 2055 and completely replaced by the clean capital by the end of the century. Discrepancies generated by not allowing adaptation (mitigation-only scenario) are here limited, as accumulation paths (of dirty and clean capital, respectively) are almost identical in these two scenarios. In other words, the presence of a low-effective[5] adaptation strategy does not interfere with the adoption of clean technologies and the transition towards a new (cleaner) economy.

As far as adaptation capital is concerned, it does not of course accumulate in the mitigation-only scenario (where the adaptation option is not available). Both in the adaptation-only and combined scenarios, adaptation is used after 2065, where the accumulation of adaptation capital (K_3) reaches immediately its maximal level ($K_{3\max}$) and stays at this level afterwards. In this two scenarios, the delay in implementing adaptation measures results from the low-effectiveness of adaptation and signs a trade-off between costs of adaptation and its positive effect on welfare. In Section 4.1, we test for different values of adaptation effectiveness and find that, when it is high, adaptation behaves as a mitigation substitute, at least for a certain

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[5] Recall that in our standard setting, at most only 33% of damages can be avoided.

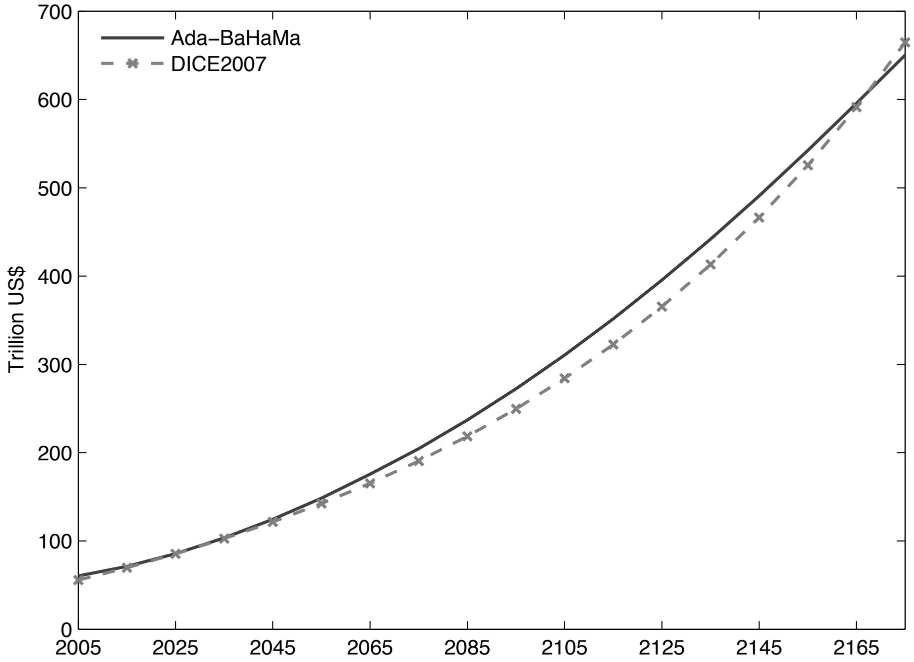

Figure 3: Economic production paths in Ada-BaHaMa and DICE2007.

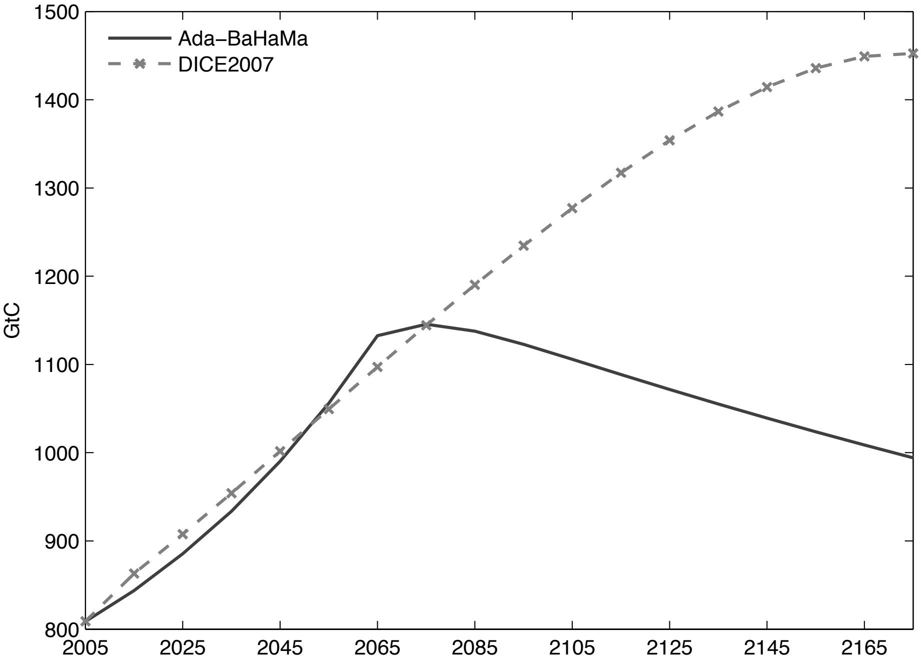

Figure 4: GHG concentration paths in Ada-BaHaMa and DICE2007.

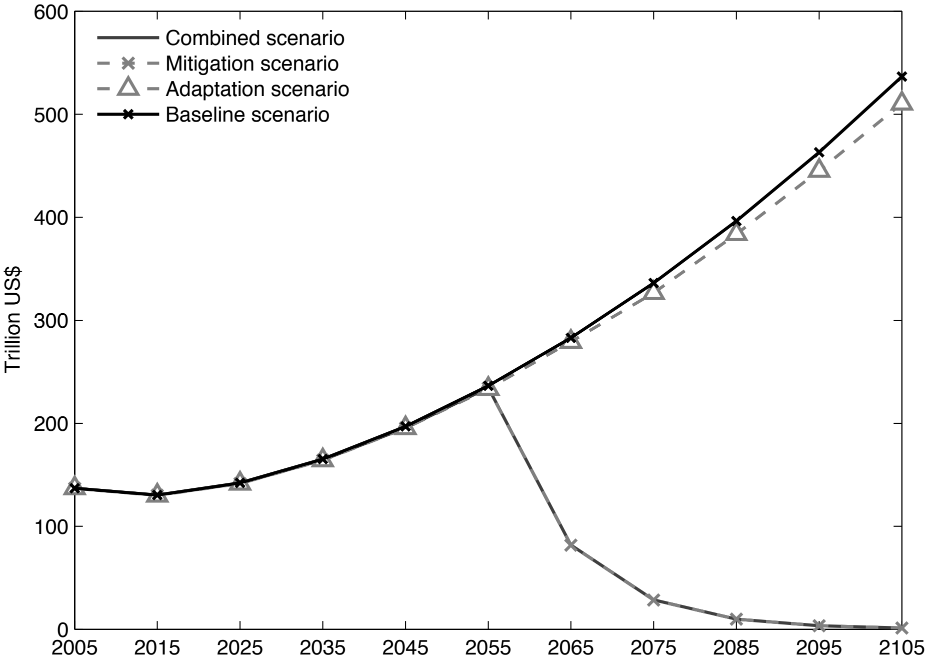

Figure 5: “Dirty” capital K_1 accumulation paths.

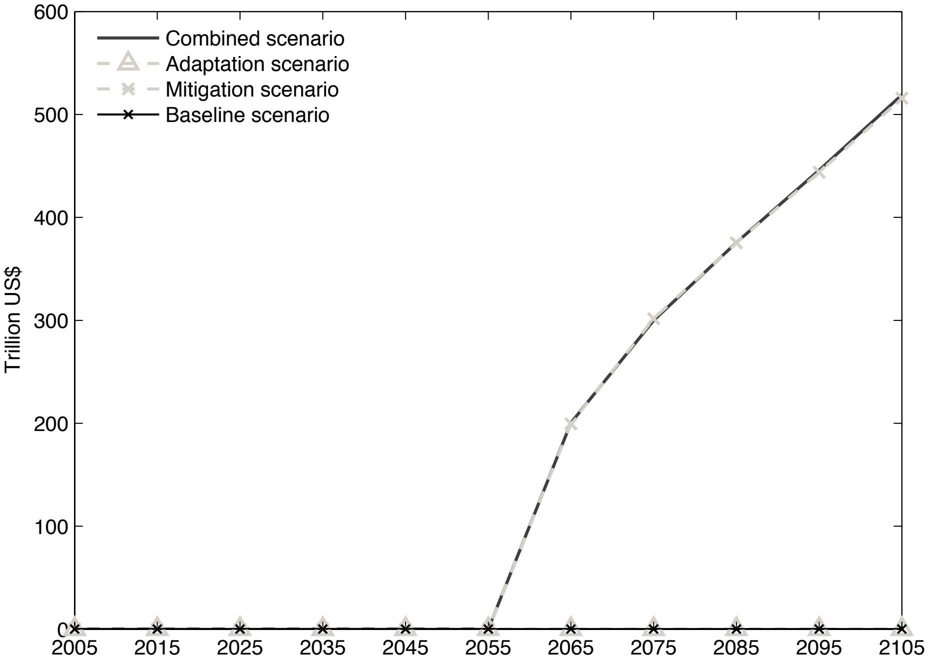

Figure 6: “Clean” capital K_2 accumulation paths.

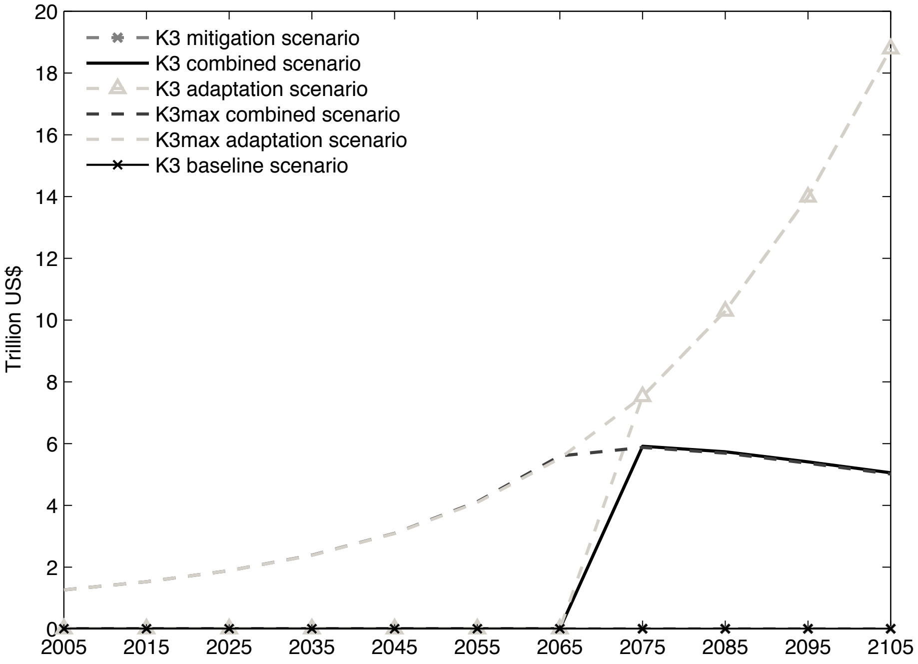

Figure 7: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$).

period. Notice also that the maximal level of adaptation capital ($K_{3\max}$) depends on GHG concentration; cf. Eq. (7). As the latter reaches much lower levels in the combined scenario (where the transition to the clean economy significantly reduces GHG concentrations; cf. Fig. 8), the required amount of capital for a maximal effectiveness of adaptation is much reduced in this scenario (compared to the adaptation-only scenario).

3.2 GHG concentration and net damages

Greenhouse gas concentration in the atmosphere, given in Fig. 8, follows the mitigation efforts explained in the previous Section 3.1. Thanks to the adoption of clean technologies (after 2055) and the corresponding transition toward a cleaner economy, concentrations in both mitigation-only and combined scenarios peak in 2075 and never exceed 1140 GtC (about 540 ppmv). Conversely in the adaptation-only scenario, where the only mitigation effort corresponds to a small reduction in dirty production (compared to the baseline), concentration keeps always increasing to reach around 1490 GtC (about 710 ppmv) by 2105.

GHG concentrations translate directly into gross damages; cf. Eq. (5). Hence as reported in Fig. 9, net damages in the mitigation-only scenario (that correspond to gross damages in the absence of adaptation) peak in the second half of the century before decreasing. Gross damages may however be "reduced" through adaptation. In the adaptation-only scenario, net damages are initially reduced (by 2075, compared to the mitigation-only scenario) when adaptation measures start to be implemented. But as they immediately reach their full potential (33% of gross damages avoided) they cannot afterwards compensate for the continuous increase in GHG concentrations and thus in damages. When both adaptation measures and adoption of clean technologies are enacted in the combined scenario, it is interesting to note that exposure to damages is the lowest of all scenarios.

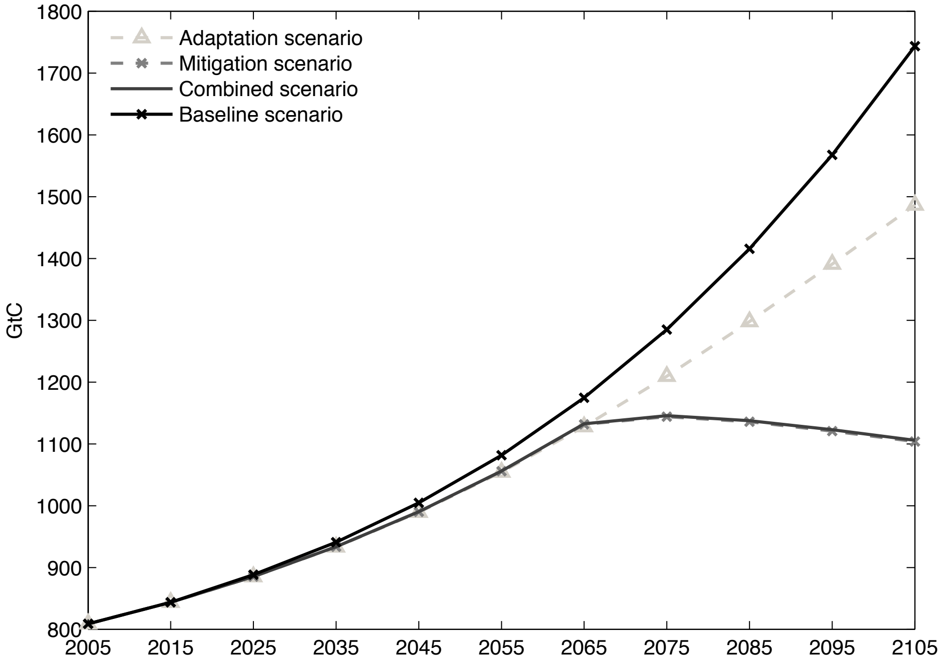

Figure 8: GHG concentration paths.

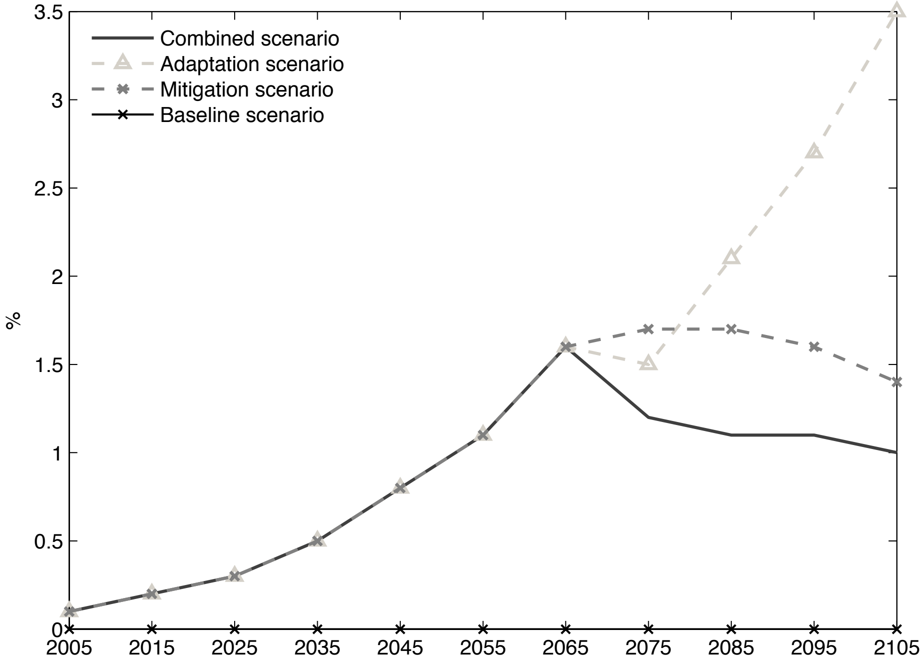

Figure 9: Evolution of net damages.

3.3 Economic output paths

Recall that in the combined scenario, economic output (Y) is calibrated on the DICE2007 model; cf. Section 2.2, Fig. 3. Compared to our baseline, we can however note the occurrence of GDP losses due to climate change damages. In Fig. 10, the combined scenario is used as a comparative level. As expected, reducing the choice of policy options to address climate changes yields an overall decrease in economic output compared to the combined scenario. This is in particular the case in the adaptation-only scenario, where the inability to prevent significant GHG concentration increases and thus significant net damages yields increasing GDP losses. The decrease in economic output is however not significant in the mitigation-only strategy (at least for the short- to medium-term), where it amounts to an average of 0.03% (per period of 10 years) between 2015 and 2085. In the longer term, it starts being noticeable with an average reduction of economic output of 0.2% between 2085 and 2105. In that case, preventing the use of adaptation measures is indeed not very disadvantageous for the economy due to our low setting for adaptation effectiveness (at most only 33% of damages can be avoided). Note also that the short-lived positive deviation observed around 2075 occurs at a time when a massive investment is done in the adaptation capital (to the detriment of investments in production capitals).

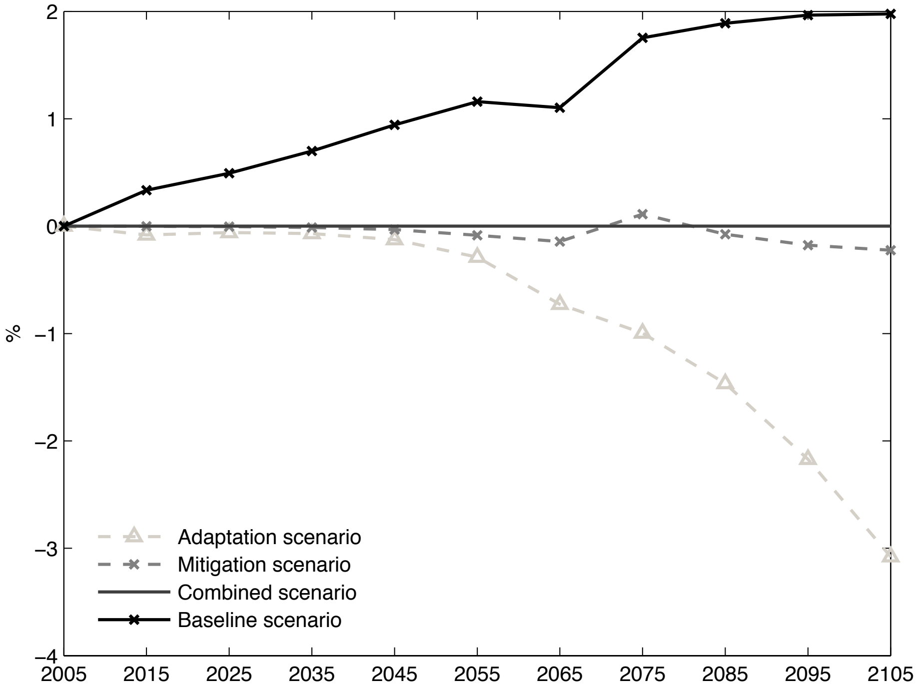

Figure 10: Economic output difference (in %) relative to the combined scenario.

4 Sensitivity analysis

The influence played by adaptation measures on the timing of adoption of clean technologies is largely dependent on certain key parameters, like the degree of adaptation effectiveness or the discount rate used in our cost-benefit analysis. In sections 4.1 and 4.2, we test for different levels for these two key parameters.

4.1 Sensitivity analysis on adaptation effectiveness

According to past and current research on adaptation policies, it seems indisputable that the effectiveness of adaptation measures will be highly influenced by geographical, political and societal idiosyncrasies, as well as by the quality and reliability of preventive efforts which in turns largely depend on the accuracy of damage predictions. Considering the high level of incertitude surrounding damage assessments, our basic parameter setting uses a relatively low level of effectiveness for adaptation. As such, it penalizes regions for which adaptation could be both inexpensive and efficient. The World Bank[6] (Margulis and Narain, 2009) indeed reports that adaptation in developing countries could be completely effective and offset climate change damages in full. Although possibly over-optimistically, an effectiveness level of 100% ($\alpha_{\mathrm{AD}} = 1$) can thus be also envisioned (if only to test the view of Margulis and Narain, 2009).

When increasing the adaptation effectiveness, we observe a strong substitution effect between increasingly efficient adaptation measures and adoption of clean technologies. As depicted in Fig. 11 and 12, the adoption of clean technologies is delayed by a few decades and its preventive role against climate change damages is replaced by adaptation measures.

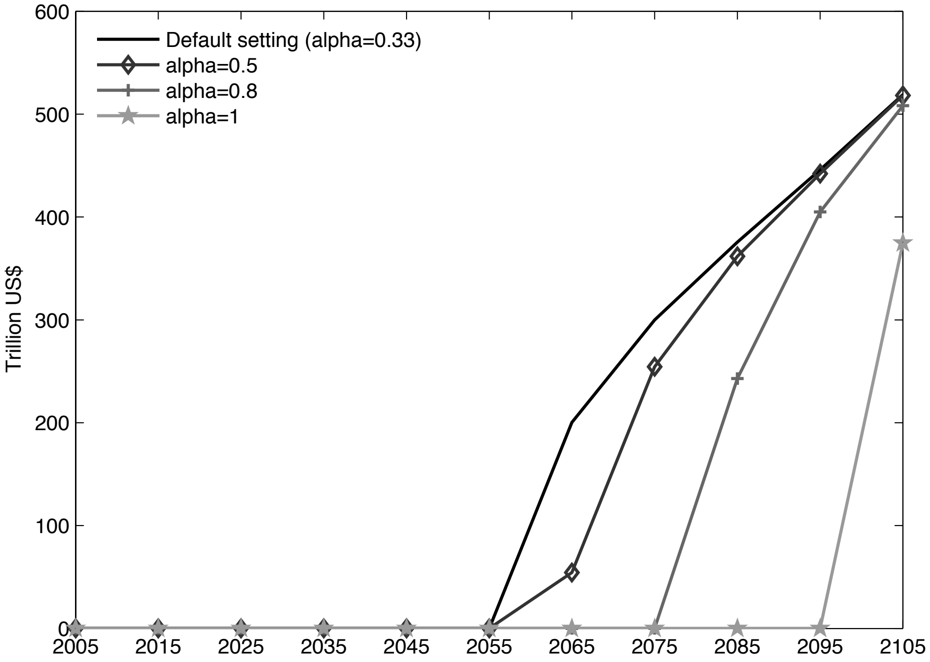

Figure 11: “Clean” capital K_2 accumulation paths for different levels of adaptation effectiveness.

Note that a stronger reliance on adaptation has the drawback of pushing GHG concentrations to much higher levels. For instance, with a value of 100% for the adaptation effectiveness, GHG concentration reaches by 2105 around 1650 GtC (about 785 ppmv, compared to 525 ppmv under our standard setting). By shielding the world’s economy from (most of) climate change damages, improvement in adaptation effectiveness favors more polluting practices and delays a transition toward a cleaner economy. This could however turn out to be a risky policy, especially in presence of uncertainty about climate change effects, which may include “abrupt” changes[7] (see for instance Lenton et al., 2008), and about the capacity to successfully–and continuously–provide efficient adaptive solutions in the future.

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[6] Which provides our cost estimates for the calibration of the maximal amount of efficient adaptation capital $K_{3\max}$.

[7] Examples of such extreme events include a melting of the West Antarctic ice sheet and a collapse of the Atlantic thermohaline circulation.

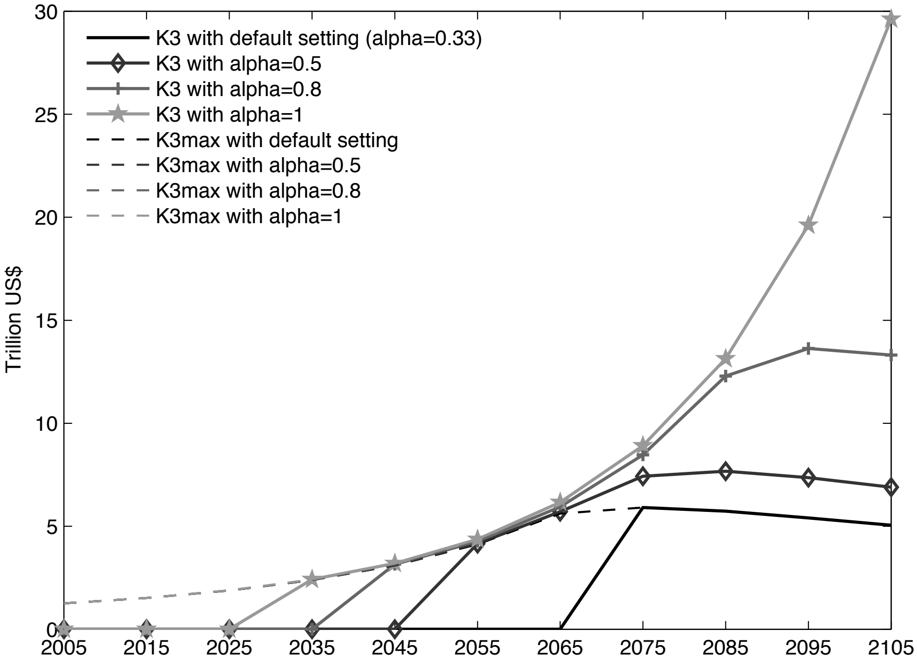

Figure 12: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$) for different levels of adaptation effectiveness.

4.2 Sensitivity analysis on the discount rate

The discount rate (used to compute the overall welfare) is one of the most debated parameter in environmental economics for its moral implications. It represents indeed the degree of disinterest current generations manifest for the lot of future generations, therefore embedding the degree of unfairness promoted by society. In the context of IA models for climate policy design, the determination of an "ideal" discount rate has resulted in extensive debates among leading economists. Stern (2006) for instance considers that a socially adequate discount rate should be close to zero (using in its review a discount rate of 0.1% per year) whereas Nordhaus (2007) uses a rate[8] between 4% and 5%. In comparison, our default setting (5%) is tilting towards the present generations. In an attempt to get clearer evidence on effects of our discount rate ρ, we test here for different levels: 3%, 7.5% and 10%.

Impacts on adoption of clean technologies and adaptation measures are given in Fig. 13 and 14.

Contrary to the previous sensitivity analysis on adaptation effectiveness, higher discount rates do not trigger a substitution effect, but a delay that affects both the adoption of clean technologies and the use of adaptation measures. Here again, clean technologies eventually replace the dirty ones. However, the higher the discount rate, the latter this transition takes place. Besides, adaptation with its low effectiveness ($\alpha_{\text{AD}} = 0.33$) is again limited to be a complement strategy to mitigation efforts, and its investment timing follows somehow the one in clean technologies.

Delaying the adoption of clean technologies has obvious impacts on GHG concentrations that reach higher levels with longer delays in adoption. For instance, under a 7.5% discount rate GHG concentration reaches by 2105 around 1280 GtC (about 610 ppmv), and under a 10% discount rate around 1420 GtC (about 675 ppmv), compared to 525 ppmv under our standard setting. Economics effects are likewise sizeable. In

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[8] Note that Nordhaus (2007) dedicates a chapter to this discount rate issue and to the reasons of its divergence with the Stern's Review.

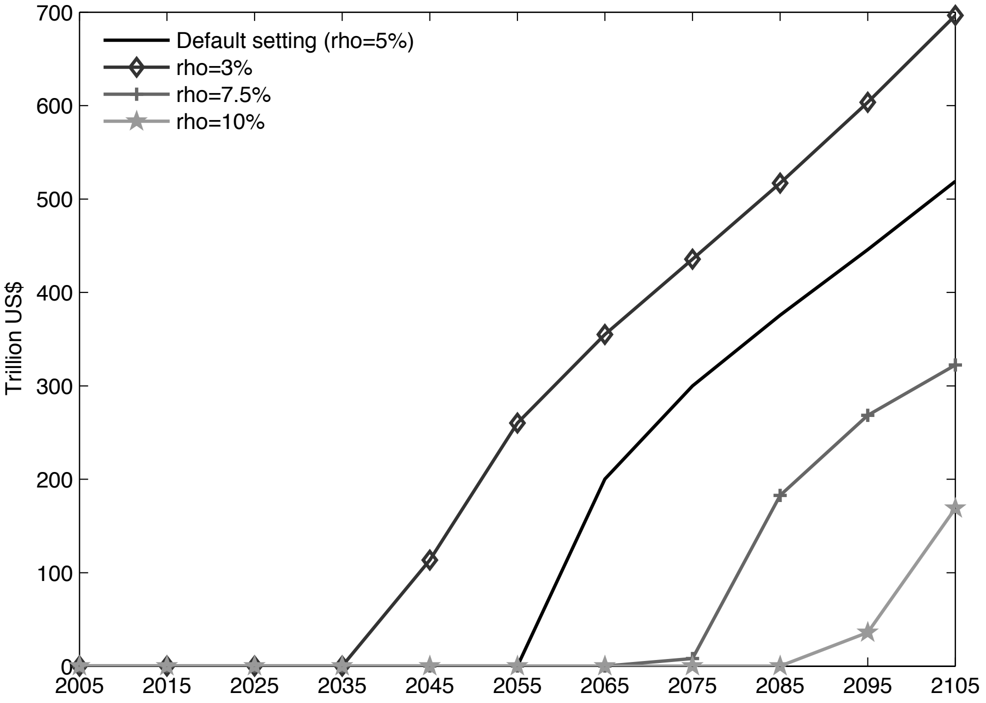

Figure 13: “Clean” capital K_2 accumulation paths for different discount rates.

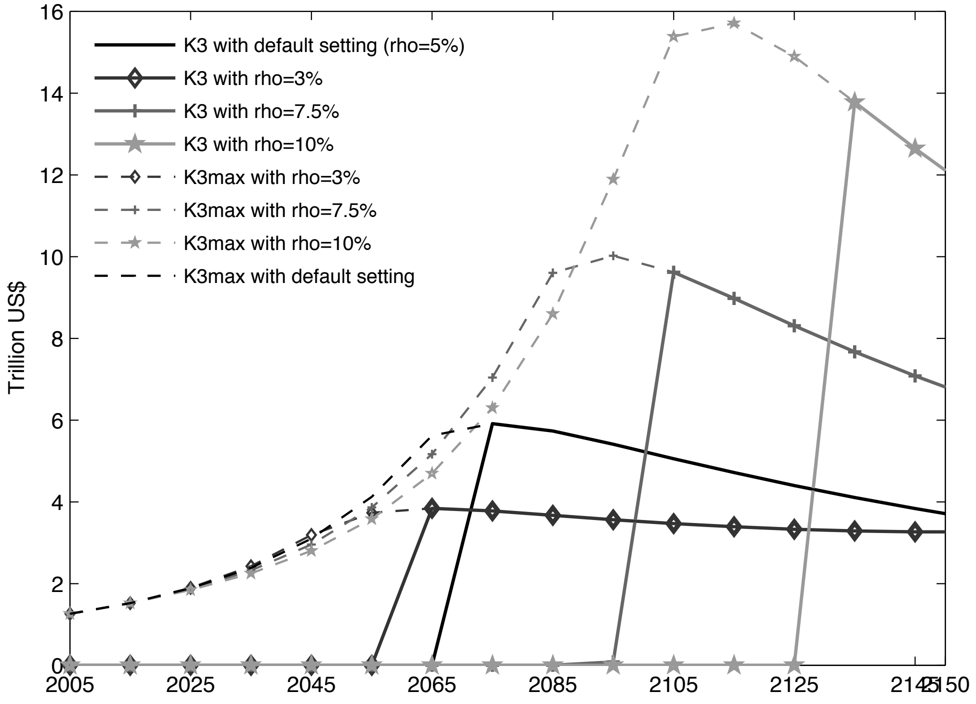

Figure 14: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$) for different discount rates.

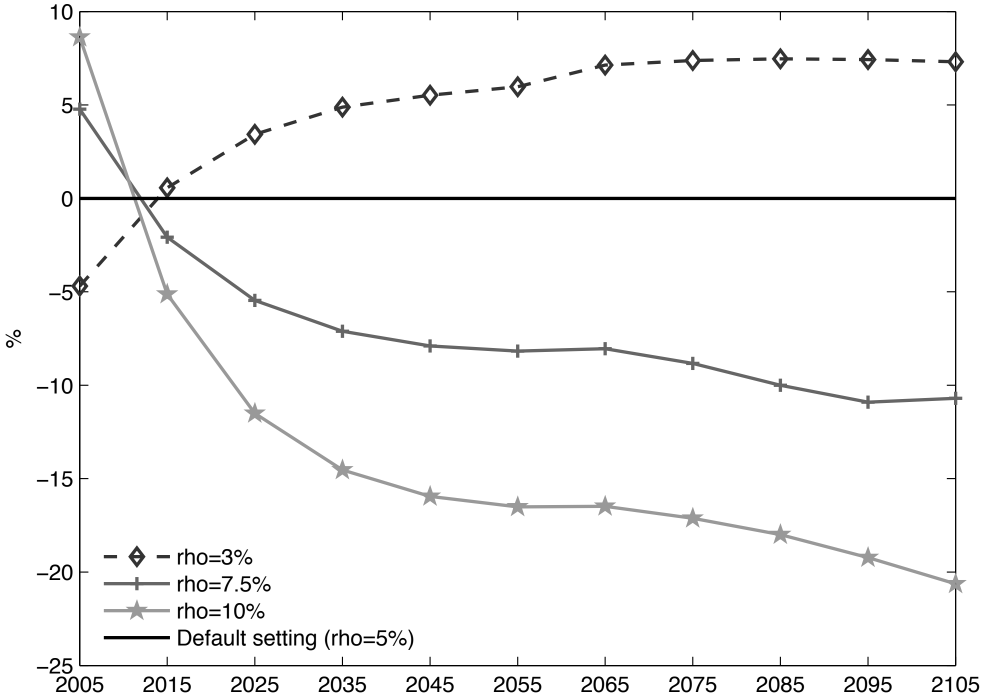

Figure 15: Consumption paths for different discount rates expressed in % difference relative to the default setting ($\rho = 5\%$).

particular, as depicted in Fig. 15, under a higher discount rate (7.5% and 10%), short-term consumption is higher (due to the increase use of less expensive dirty capital) at the expense of medium- to long-term consumption (reduced due to higher climate change damages). Conversely, under a lower discount rate (3%) the faster transition to a clean economy yields from 2025 on higher consumption levels.

Such trade-off between short-term benefits and medium-to-long-term benefits is also revealing of our particular framework involving technology-shifting mitigation. To ensure a fast transition, high discount rate should not be used in economic computations. From that perspective, subsidizing promising new technologies seems to be justified, at least to compensate for higher discount rate applied to riskier investments.

5 Conclusion

In this paper, we introduce both adaptation and mitigation strategies as decision variables in an integrated assessment model and assess their respective economic and environmental impacts as well as their influence on each other.

Our model presents several differences with the current literature on adaptation and mitigation in IAM. First, we consider adaptation as a proactive policy requiring investment in (an adaptation) capital, which is a richer framework than the reactive cost often seen in the literature. Second, and contrary to the approach retained by de Bruin et al. (2009b) in which adaptation and mitigation decisions are separable, our framework allows for interaction between them. Indeed, we model the required adaptation investment as being dependent on the carbon concentration level and thus on the mitigation strategy deployed. And third, we model mitigation as a costly transition towards clean production systems. This sheds light on trade-offs between existing (fossil) technologies and new cleaner (renewable or fossil with carbon capture and sequestration) production systems.

We find that interaction between adaptation and mitigation is complex and largely dependent on their respective attributes. Our results show that adaptation, when weakly effective, is only used as a late complement to mitigation strategies. Investments in adaptation lag behind those in clean production systems and do not prevent an early transition from dirty to clean technologies (in our combined scenario). However, resorting to an adaptation-only strategy causes significant GHG concentration increases and thus significant net damages that yield increasing GDP losses. Sensitivity analysis reveals however that this situation changes with increasing adaptation effectiveness. In particular, highly effective adaptation acts as a short- to medium-term substitute to mitigation efforts, but without preventing long-term investments in clean production systems. Sensitivity analysis on the discount rate indicates also that choosing a rate is certainly not innocuous on the policy recommendations. In our framework, higher rate values have in particular the effect of postponing both mitigation and adaptation efforts.

We view this paper has an essential (first) step for implementing adaptation in the BaHaMa model. But we do envision several other steps to enrich the modeling framework of Ada-BaHaMa, to be carried out in future research. On the one hand, an important step will be to introduce uncertainty, for instance on the magnitude of climate change damages, on the adaptation effectiveness or on a technological breakthrough that would provide access to the clean economy. As in Bahn et al. (2008), the resolution of uncertainty will be model as a stochastic control problem. On the other hand, we also acknowledge that the choice of adaptation and mitigation policies has to take into account heterogeneity in regional costs, exposures and achievable benefits. A further improvement of our model will be the development of a multi-regional version of Ada-BaHaMaA, building on the two-region version of BaHaMa reported in Bahn et al. (2010).

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