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Adaptation, Mitigation and "Green" R&D to Combat Global Climate Change. Insights From an Empirical Integrated Assessment Exercise

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Working Paper

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Summary
This work develops a framework for the analysis at the macro-level of the relationship between adaptation and mitigation policies. The FEEM-RICE growth model with stock pollution, endogenous R&D investment and emission abatement is enriched with a planned-adaptation module where a defensive capital stock is built through adaptation investment. Within this framework the optimal path of planned adaptation, the optimal inter and intra temporal mix between adaptation, mitigation and investment in R&D, and the sensitivity of a strategy to each other is identified. The major conclusions of this research show that adaptation, mitigation and R&D are strategic complements as all concur together to the solution of the climate change problem; nonetheless the possibility to adapt reduces the need to mitigate and partly crowds out other forms of investment like those in R&D. The optimal intertemporal distribution of strategies is also described: it requires to anticipate mitigation effort that should start already when climate damages are low and postpone adaptation intervention until they are substantial. Thus the possibility to adapt is not a justification to delay abatement activities. A sensitivity analysis demonstrates the robustness of these results to different parameterizations, in particular to changes in expected climate-change damages and in the discount rates.

Keywords: Climate change impacts, mitigation, adaptation, integrated assessment

JEL Classification: Q25, Q28

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1. Introduction and Background.

Since the rising of a global warming concern, the idea of adaptation backed that of mitigation.

When in 1992 the Rio UN Framework Convention on Climate Change was signed, its famous art. 2 stated the aim to stabilising "…greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Because of the recognised role of anthropogenic influence on climate change, the policies mentioned first were the so-called mitigation strategies: namely those devoted to the reduction of greenhouse gas emissions and concentration in the atmosphere

However the perception of the role potentially played by "adaptation processes" was already embedded in the Convention work. Art 3.3 continued saying: "The Parties should take precautionary measures to anticipate, prevent or minimise the causes of climate change and *mitigate* its adverse effects". Anticipate the causes and mitigate adverse effect indeed described adaptation.

In fact, all the attention was initially captured by the general commitments accepted by developed countries to reduce their GHG emissions to 1990 levels by the year 2000.

For instance, in the mid nineties, paramount interest was raised by the Contribution of Working Group III to the 1995 IPCC Second Assessment Report (SAR) analysing costs and benefits of mitigation policies. Much less vocal were the indications of SAR Working Group II which emphasised clearly the role of adaptation affirming: "Policymakers will have to decide to what degree they want to take precautionary measures by mitigating greenhouse gas emissions and enhancing the resilience of vulnerable systems by means of adaptations".

There are several reasons for this that can be summarised in the following:

- lack of theoretical and practical knowledge about the nature and processes of adaptation, which is also an effect of the limited attention given to adaptation by the policy and scientific communities (Klein *et al.*, 2003);
- more familiarity of policy makers (and social scientists) with the economic instruments usually adopted to implement mitigation measures, like taxes, quotas and tradable emission permits, than with those required to foster adaptation measures (e.g. technology transfers, project based development aid etc.)
- the fear that adaptation - typically working on smoothing negative effects - would have decreased the perception of the danger posed by global warming with negative consequences on the effort and commitment to limit it (Wilbanks, 2005).

Since then, two facts contributed gradually to increase the attention on adaptation issues.

Firstly, increasing recognition of strong climate inertia highlighted that even in the presence of strong mitigation policies some degree of climate change would have been inevitable. Thus mitigation, although essential to limiting the extent and probability of a potentially harmful climate change, could not respond to the problem of coping with the "residual" or "unavoidable" change.

Secondly the decided GHG reduction objectives and the associated mitigation policies proved to be much more difficult to be implemented than expected. The 1997 Kyoto Protocol itself, posing binding commitment to GHG emissions of developed countries, and saluted as a great diplomatic success, in reality recognised that the Rio voluntary targets were too ambitious switching ten years into the future (in the 2008-2012 "first commitment period") the reduction effort. Moreover, the post-Kyoto negotiation rounds, bridging parties from the signature to the ratification, saw the defection of important developed countries like the USA and initially Australia and are still unable to foster a strong participation by developing countries.

All this spurred the research of alternative responses to climate change; in particular toward adaptation. Probably the most known definition of adaptation is that provided by the 2001 IPCC Third Assessment Reports (TAR): "adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli, and their effects or impacts".

The whole Contribution of Working Group II to the TAR focussed on "Impacts, Adaptation and Vulnerability". It concludes [p. 879]: "…Adaptation to climate change has the potential to substantively reduce many of the adverse impacts of climate change and enhance beneficial impacts…" nevertheless [p. 880]: "…Current knowledge of adaptation and adaptive capacity is insufficient for reliable predictions of adaptations; it also is insufficient for rigorous evaluation of planned adaptation options, measures and policies of governments".

Since then, notwithstanding new scientific evidences and the growing literature in the field, this knowledge gap has not been fulfilled yet. According to the 2006 Stern review: "…more quantitative information on the costs and benefits of economy-wide adaptation is required…" given that "Only a few credible estimates are now available of the cost of adaptation…and… highly speculative".

The 2007 Fourth Assessment Report of the IPCC concludes that [p.737]: "… there is […] a need for research on the synergies and trade-offs between various adaptation measures, and between adaptation and other development priorities. […] Another key area where information is currently very limited is on the economic and social costs and benefits of adaptation measures".

Similarly the 2007 EEA report on “Cost of Adaptation” claims [p. 57]: “There is little information in fact that shows (a) how adaptation costs compare to the potential damages of not adapting and (b) how the adaptation costs would change if there were more mitigation. […] Major advances are needed in the economic analysis of adaptation”.

A sample of selected open questions can be the following:

- How effective can be adaptation in reducing climate-change damages?
- How much will it cost (in absolute terms and compared with other strategies)?
- When – where and what adaptation strategies should be adopted (should damage be anticipated or simply awaited and then accommodated? Should resources for adaptation be addressed where they can be more effective or where they are more needed?)?
- Who should adapt and bear the costs (private agents or public agencies)?
- How to harmonise adaptation with other strategies? In particular are mitigation and adaptation complements or substitutes? Does mitigation reduce or increase in the presence of adaptation? What is the optimal intra and intertemporal balance between them? What determines this balance?

This paper tries to shed some light on the last strand of questions. In the specific the relationship between mitigation and adaptation is analysed using an empirical integrated assessment model properly modified. Trade-off and complementarity of the two strategies are highlighted offering some qualitative indications about their optimal mix.

In what follows, section 2 introduces the theoretical and empirical literature on adaptation and mitigation joint modelling, section 3 describes the modelling approach adopted by this study, section 4 presents main results, section 5 proposes selected sensitivity tests and finally section 6 concludes.

2. Modelling the relationship between mitigation and adaptation

In our knowledge only two studies offer a theoretical framework describing the combination between mitigation and adaptation. In a linear programming framework Ingham et al. (2005) determine the conditions under which the two options are economic substitutes or complement. Under standard conditions the two strategies are substitutes i.e. a reduction in the cost of one increases its use and decreases that of the other. This result is robust to the introduction of uncertainty and holds in partial and general equilibrium as well as in a static and dynamic setting.

Mitigation and adaptation can be complements in the unlikely occurrence that mitigation influences the marginal adaptation costs. Complementarity may arise also because of catastrophic events when mitigation, as a mean to reducing the risk of the catastrophe, also helps adaptation to occur. Linear programming is also chosen by Lecoq and Shalizi (2007), to study the relation between mitigation, anticipatory and reactive adaptation. They demonstrate the substitutability of mitigation and adaptation which claims for a joint determination of the two in international climate negotiation. They also demonstrate that the introduction of uncertainty on the amount and geographical distribution of environmental damages tends to increase cost effectiveness of mitigation, which has a global scope, with regard to adaptation, which is typically location-specific. By the same token, uncertainty favours reactive respect to anticipatory adaptation in the case the two are substitutes. However the authors conclude that substitutability or complementarity of the two forms of adaptation is very difficult to be assessed in practice.

The empirical literature is slightly more extended, though developed by few authors.

In a typical approach, benefits of a mitigation strategy are confronted with those related to a comparable adaptation intervention.

Tol (2005) within the framework of his FUND model contrasts benefit of two different emissions reduction policies, entailing a marginal abatement cost of $1/tC and $20/tC, respectively, with the environmental benefits brought by the same money spent in development aid considered a proxy for enhancement of adaptive capacity. It is shown that with modest mitigation African economies would benefit more from development aid than from abatement, while the opposite is true for Latin America. In the case of the $20/tC climate policy, all regions would be better off (for a sufficiently high discount rate) with development aid than with abatement.

This result suggests that investing in development, particularly in the poorest countries, may well be a better strategy for reducing the impacts of climate change than emission abatement.

Tol (2007) analyses mitigation/adaptation interactions in the context of sea-level rise. An optimal coastal protection module that balances efficiently costs and benefits is included in FUND and different scenarios with and without mitigation are compared. Adaptation to sea level rise emerges as a cost-effective way to reduce sea level rise damages and almost all countries opt for full protection as of 2025. The introduction of a mitigation policy stabilising CO_2 concentration at 550 ppm., reduces the need to adapt: lower emissions and lower temperatures imply lower sea-level rise and lower and less expensive dikes. However the momentum of sea-level rise is so large that mitigation cannot avoid more than the 10% of dry and wet land loss at the global level. This in turn implies only a negligible effect in terms of lower economic damage due to land loss (roughly -10%)

and especially in terms of lower expenses in coastal protection which at the world level remain nearly unchanged. In addition, mitigation costs. These costs amount to an average of 10% and of 5% of the benefits of emission reductions for dry lands and wetlands, respectively. Accordingly mitigation seems not to be an alternative to adaptation. This points the need to balance carefully the two strategies also because mitigation crowds out resources to adapt.

Finally Tol and Dowlatabadi (2001) focus on the trade off between mitigation and adaptation in the specific case of malaria in Africa. They show that an increased mitigation effort can in principle reduce malaria mortality as a result of a slower rate of warming (-4% of deaths over the 21st century in the case of a Kyoto-like emission reduction policy). Nevertheless, the assumed negative economic consequences of abatement policies, resulting in reduced growth rates in OECD economies, rebound negatively on developing countries and particularly on the African economy . Because of lower international aid and worsened trade relationships, Africa becomes poorer and thus more vulnerable to (climate-induced) malaria. Taking this into account the Kyoto Protocol might potentially *increase* malaria mortality by 4%. In a world of scarcity, alternative strategies to combat climate change entail opportunity costs: more resources devoted to mitigation lower the resources available for adaptation. This *per se* calls for an integrated policy.

These studies, although innovative and a step forward respect the existent, present one or both of the following shortcomings. Firstly, like in the case of sea level rise or health, mitigation is compared with just one specific adaptation strategy; secondly, mitigation and adaptation do not appear within the same modelling framework as available strategies in the hand of an optimising decision makers. This prevents to find the optimal balance between the two weighting respective costs and benefits.

Two modelling exercises try to do this.

The first is the PAGE model (Hope, 1993, 2007) where different levels of adaptation can be imposed to the macro-regional economic systems analysed and their additional costs and benefits compared into a climate-change impact assessment exercises. A maximum rate of change (slope parameter) and a maximum absolute change (plateau parameter) in global temperature are assumed to be sustainable without considerable damages. Adaptive policies operate in three ways: they increase the slope of the tolerable temperature profile, its plateau, and finally they can decrease the adverse impact of climate change when the temperature eventually exceeds the tolerable threshold. However adaptation is exogenously imposed and costs and benefits are given: the “default” adaptation strategy of the model for instance estimates a costs for the economic sector in the EU of 3, 12 and 25 US billion$/year (min., mode and max. respectively) to increasing of 1°C the temperature tolerability and of additional 0.4, 1.6, 3.2 US billion $/year to achieve a 1% reduction in climate change impacts. At the world level this implies, at a discount rate of the 3%, a cost of nearly 3 trillion of US $ to achieve a damage reduction of roughly US $35 trillions within the period 2000-2200. Impact reduction ranges from the 90% in the OECD to the 50% elsewhere. With the given assumptions, PAGE could easily justify aggressive adaptation policies (see e.g. Hope *et al.*, 1993). Due to the huge uncertainty about cost and effectiveness of adaptation, more than questioning the credibility of these assumptions, it is worth emphasising that, in PAGE adaptation is exogenous: not determined by the model, but decided at the outset.

The second is proposed by de Bruin et al. (2007). They enrich the Nordhaus (1994) DICE model with explicit cost and benefit functions of a world adaptation strategy, whose parameters are calibrated according to available knowledge. In their framework, the rate of adaptation becomes a control variable whose optimal level is found equating its (cumulated discounted) marginal benefits and costs. Adaptation rates can be compared with the abatement rates, the other endogenous climate policy variable of DICE. This way also the optimal mix between the two can be found.

De Bruin et al. (2007) model adaptation as a flow variable: it needs to be adjusted period by period (10 years in the model) but also, once adopted in one period it does "[page 7] not affect damages in the next period thus each decade the same problem is faced and the same trade-off holds".

They show that adaptation and mitigation are strategic complements: optimal policy consists of a mixture of adaptation measures and investments in mitigation, this also in the short term even though mitigation will only decrease damages in later periods. Adaptation is the main climate change cost reducer until 2100 whereas mitigation prevails afterwards. In addition, it is shown that benefits of adaptation are higher than those of mitigation until 2130. Finally authors highlight the trade off between strategies: the introduction of mitigation decreases the need to adapt and *vice versa*, however the second effect is notably stronger than the first.

The present study is similar in some respect to this last contribution, but with some basic differences.

Firstly, adaptation is a cumulating stock. Decision makers can build "defensive capital" or adaptive capacity over time (think for instance to coastal protection or climate proving infrastructures). Albeit subjected to a depreciation rate, they do not disappear each period, but need to be adjusted to increasing damages. Thus the "flow dimension" of adaptation is considered (periodical investment), together with a "stock" nature. This modelling approach captures the dynamic interaction between climate-change damage and protection which have both the nature of stocks, moreover emphasises the difference between adaptation, and mitigation which has a typical flow nature.

Secondly, this study adds the role of technical progress. An R&D investment is an additional policy variable that the decision maker can use either to increasing output or decarbonising production. Indeed it appears useful to introduce this further dimension analysing the policy mix adaptation/mitigation in the light of the crucial role assigned to technological improvement in any climate-change policy debate.

3 The Modelling Exercise

3.1 The model

In this exercise an adaptation module is added to the FEEM-RICE model (Buonanno et al. 2000) an enriched version of the Nordhaus and Yang (1996)'s RICE96 model, allowing for endogenous technical progress.

It is a hard linked climate economic Ramsey-Keynes growth model where the world is divided into six macro regions (USA, Japan, Europe, China, Former Soviet Union and the Rest of the World). In this paper the model has been run to find the full co-operative or global welfare solution. That is it is assumed that a central planner maximises the aggregate world utility represented by the (weighted) sum of regional utilities.

When all options are available, she chooses the optimal path of investment in physical capital, investment in R&D, abatement and adaptation to maximise the discounted value of per capita consumption flow of her representative household.. The economic side of the model presents a constant return Cobb-Douglas production function combining labour capital and technology to produce output. Population (taken to be equal to full employment) grows exogenously over time, whereas capital accumulation is governed by the optimal rate of investment.

Two different treatments of technical progress are then considered. In the first an exogenous Hicks neutral technological factor is imposed, its initial values correspond to the observed rates for 1960-1990, then it declines exponentially over time. "Green" technical progress is modelled as well, it has the form of a "decarbonization" parameter specified as energy augmenting Autonomous Energy Efficiency. In a second proposed extension (Buonanno et al. 2000) endogenous technical change affects factor productivity. This is done by adding a "stock of knowledge" depending on an endogenous investment in R&D as a productivity multiplier to each production function. Moreover induced technical change affects also the emission-output ratio determining the degree of "decarbonisation" of the economic system.

The original version of the model is specifically suited to consider the mitigation option represented by emission reduction. This is modelled as a wedge between output gross and net of climate change effects, the size of which is dependent on the amount of abatement (entailing costs in term of resources diverted from production to abatement activities) as well as the change in global temperature (provoking costs in terms of lower output due to environmental damage).

The environmental part of the model converts the CO_2 emission flow - undesired by-product of production activity - in increase of CO_2 concentration on its turn determining radiative forcing and finally temperature.

3.2. Implementing an adaptation module

The full set of equations of the FEEM-RICE model is reported in appendix. Below is the description of the adaptation module.

Adaptation is a further form of investment and takes the form of an explicit long-term program decided by a fully rational decision maker. An additional state variable representing the stock of adaptation $SAD(n,t)$ region and time specific is thus added. The law of motion for this new stock is:

$$SAD(n,t+1) = (1-\delta_A)SAD(n,t) + IA(n,t) \tag{1}$$

where δ_A is the depreciation rate of capital invested in adaptation and $IA(n,t)$ is the investment flow in adaptation by each region n and time t. The basic difference between investment in adaptation and "traditional" investment is that the first does not contribute to increase the capital stock in the next period entering the production function, but does contribute to reduce the negative effects on output of the temperature increase. This is done modelling the relationship between gross and net output according to the following equations:

$$Y(n,t) = \Omega(n,t)Q(n,t) \tag{2}$$

$$\Omega_1(n,t) = \frac{\left(1-b_{1,n}\mu(n,t)^{b_2}\right)}{\left(1+\theta_1 \cdot \frac{1}{\exp(SAD(n,t))} \cdot \left(T(t)/2,5\right)^{\theta_2}\right)} \tag{3}$$

with the initial condition:

$$SAD(n,0) = 0\,. \tag{4}$$

$Q(n,t)$ is gross or potential output while $Y(n,t)$ is net output. The difference between the two is represented by the coefficient $\Omega(n,t)$ which compounds three different components. The first are abatement costs: costly abatement $\mu(n,t)$ reduces net output (the higher μ the lower Ω). The second are climate-change damages: higher temperature levels $T(t)$ reduce net output (the higher T the lower Ω). Finally the third is the damage-reducing effect of adaptation: the higher the stock of capital devoted to adaptation the lower the penalisation of potential output due to climate change.

$b_{1,n}$, b_2, θ_1, θ_2, are the original coefficients calibrated by Nordhaus. They summarise quantitative and qualitative assessments about abatement costs and climate change damages in the different world regions.

According to equations (1) to (4), if no adaptation is undertaken ($SAD(n,t)=0 \quad \forall n,t$), the model reproduces the original results of Nordhaus (1996) and of Buonanno et al. (2000) for the case of exogenous and endogenous technical change respectively.

To complete the picture the allocation rule for net output now has to consider the additional investment form:

$$Y(n,t) = C(n,t) + I(n,t) + IA(n,t)$$

The formulation above incorporates two assumptions: firstly, that no planned climate-change adaptation started before 1990 which is reasonable[1]; secondly, that the RICE'96 parameterisation of the cost of climate change described by Ω does not include adaptation costs. In fact, the RICE 96 damage function does include the cost of some adaptation interventions like coastal protection. Thus, in principle, using some available information, it could be possible to disentangle these costs from total climate change damages and assume that they represent optimal adaptation in a no mitigation case. This procedure is for instance proposed by De Bruin et al., (2007). In practice, though, information on adaptation are very scarce and those on residual climatic damage still uncertain. Accordingly, any attempt to do this will be necessarily subjected to the greatest uncertainty and subjectivity. The present research thus assumes for simplicity that planned adaptation costs are not part of RICE 96 estimated damages, which does not affect the qualitative nature of the highlighted outcomes. Sensitivity analysis will then test the results' robustness to different specification of cost effectiveness of adaptation and to changes in damages.

For the same reasoning, the procedure followed to calibrate adaptation costs and benefits is very simple: it consists to setting a lower bound to the first and an upper bound to the second. It is

[1] Consider that the IPCC has been founded in 1988 and that before the issue of climate change was a restricted topic for specialists.

assumed that in 2050 total adaptation costs must be higher than 0.15% of world GDP. This data comes from extrapolations from Tol (1998) survey, Bosello et al. (2006) and Bosello et al. (2007) proposing estimates of possible ranges for the cost of a set of adaptation strategies. Figures reported by the different studies are all uniformed to a common temperature increase scenario, roughly a +1.5°C respect to preindustrial period, that the model reaches in 2050. The issue of defining a value for adaptation ability to reduce climate change damage is more controversial. Indeed effectiveness of each possible adaptation strategy depends on a variety of factors which are less clearly known than those determining costs. For instance if one can assume that coastal protection can in principle offset all the damages of climate-change induced sea level rise, thus being 100% effective, much more difficult is to quantify exactly by how much an increased health care expenditure could reduce additional climate-induced mortality. Secondly, there is the enormous problem to aggregate in one single figure the effectiveness of all possible adaptation actions that can be implemented at the global level. Accordingly, a wide range of assumptions can be (un)justified. Some indication on the potential of adaptation to offset climate change damages are however proposed for the agricultural sector by a somehow extended and consolidated literature (see for a non exhaustive list: Fisher et al., (1993); Reilly et al., (1994); Rosenzweigh and Parry, (1994); Rosenzweigh and Hillel, (1998); Antle et al., (2001); Bindi and Moriondo (2005); Easterling et al. (2007)). Surveying this literature a rough estimate of damage reducing power of adaptation in agriculture ranges from 40% to 98% of total climatic damage for a doubling of CO2 concentration. Using this indication as a guideline, this study assumes conservatively that adaptation in 2110, the year when CO2 concentration doubles in the model "no policy scenario", cannot eliminate more than the 70% of total climatic damage[2].

4 Selected Results

In what follows, four different model specifications are considered.

- The "mitigation case" where mitigation is the only strategy available to the policy maker; it is the benchmark against which all the other specifications are compared (BASE in table and figures).
- The "research and development case" where mitigation and R&D investment are both endogenous policy variables (M+R in tables and figures).
- The "adaptation case" where mitigation is coupled with adaptation (M+A in tables and figures);

[2] This data is in line with other studies on adaptation. For instance De Bruin et al. (2007) impose that in 2130 adaptation reduces climate change damage in a range of the 30% - 80%. In Hope's PAGE model adaptation offset thes 90% and 50% of total damage in OECD and in non OECD countries respectively within he period 2000-2200.

- The “Adaptation and investment in R&D case”, where the policy basket is the amplest as mitigation, adaptation and green R&D can all be used to contrast climate change (M+A+R in tables and figures)

4.1 The effects of adaptation.

When adaptation is undertaken, abatement rates are significantly lower (-25% in 2000, -80% in 2100) compared to the “mitigation only” case (see fig.1). The stock of R&D also declines (-5.8% in 2100 see fig. 2). Emissions increase (peeking to + 22 % and + 11% when investment in R&D is an option or not respectively (see fig. 3)). Notwithstanding lower abatement and higher emissions, adaptation reduces considerably the negative impact of climate change. Adaptation emerges also as a long-term option (fig.4). It starts to be appreciable after 2040 - when damage is reduced the 14% - and booms afterward - when damage is reduced up to the 50% - (see fig. 5). Note the peculiar role of R&D compared to the case when it is not a decision variable. It produces two counterbalancing effects: in the longer term it increases economic growth, emissions and damage, but it also fosters the decarbonisation of the economy decreasing emissions and damage. The first effect prevails since 2010 and between 2020-2080 with and without adaptation respectively (fig. 3). Consequently, at least until 2100, the stock of damage is higher with than without R&D (fig. 5) and a higher abatement and adaptation efforts are required (fig.1 and 4 respectively).

Fig. 1 Mitigation in the presence of other strategies: % difference r.t. mitigation only

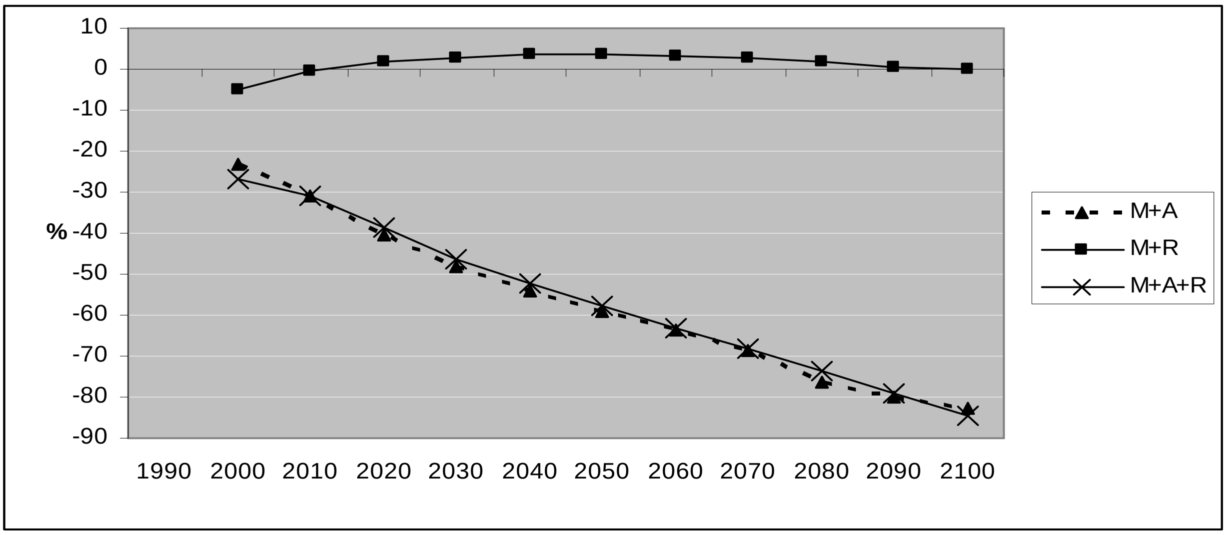


Fig. 2 Stock of R&D with adaptation: % difference w.r.t. no adaptation

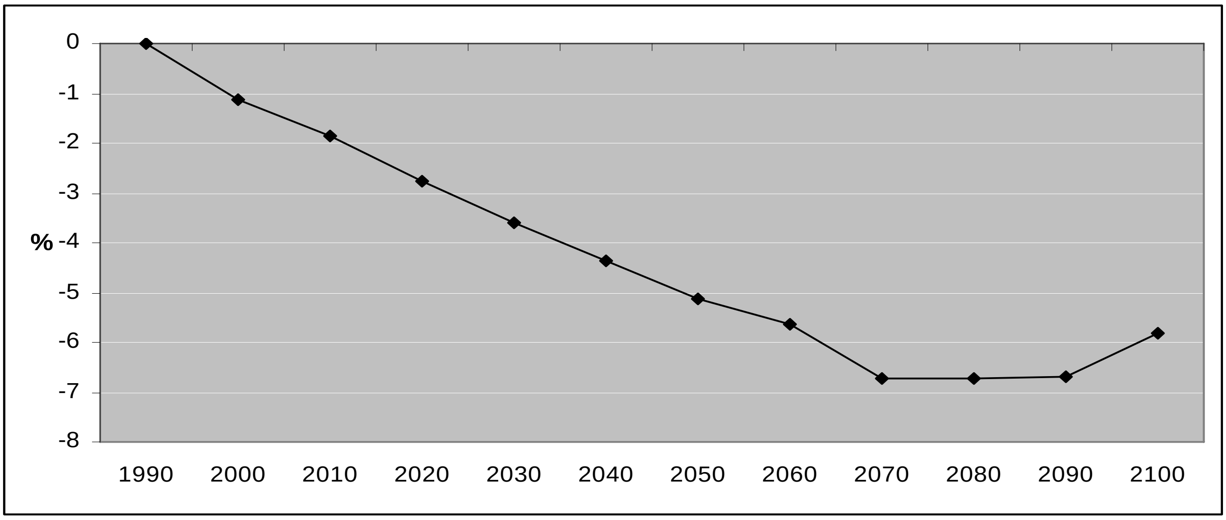


Fig. 3 CO2 emissions under different strategies: % difference w.r.t. no adaptation

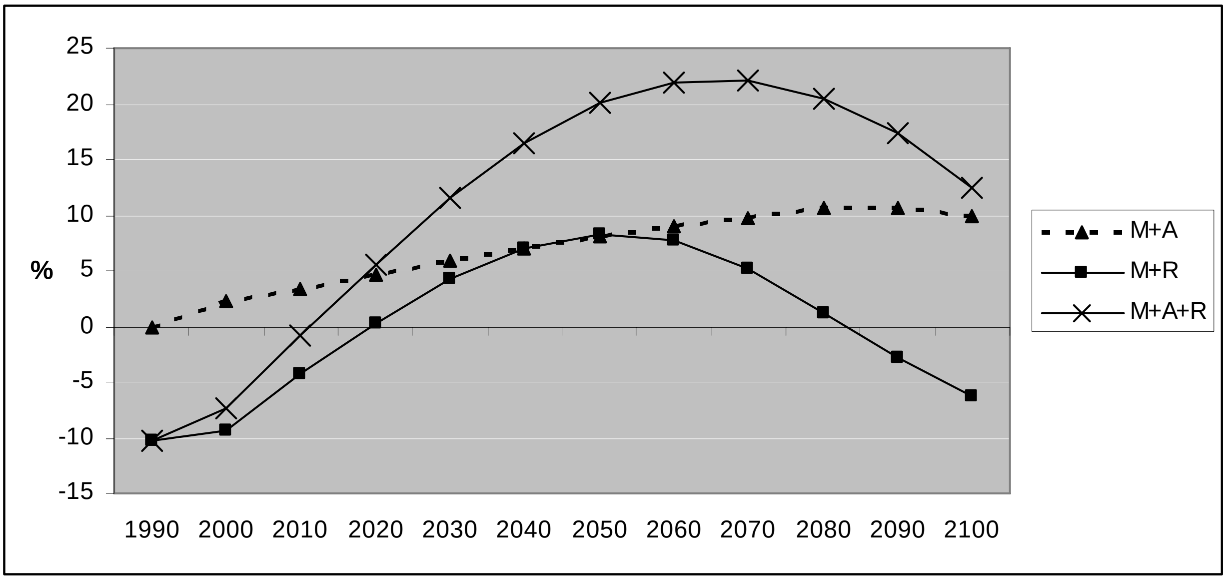


Fig. 4 Stock of defensive capital: % of total capital stock

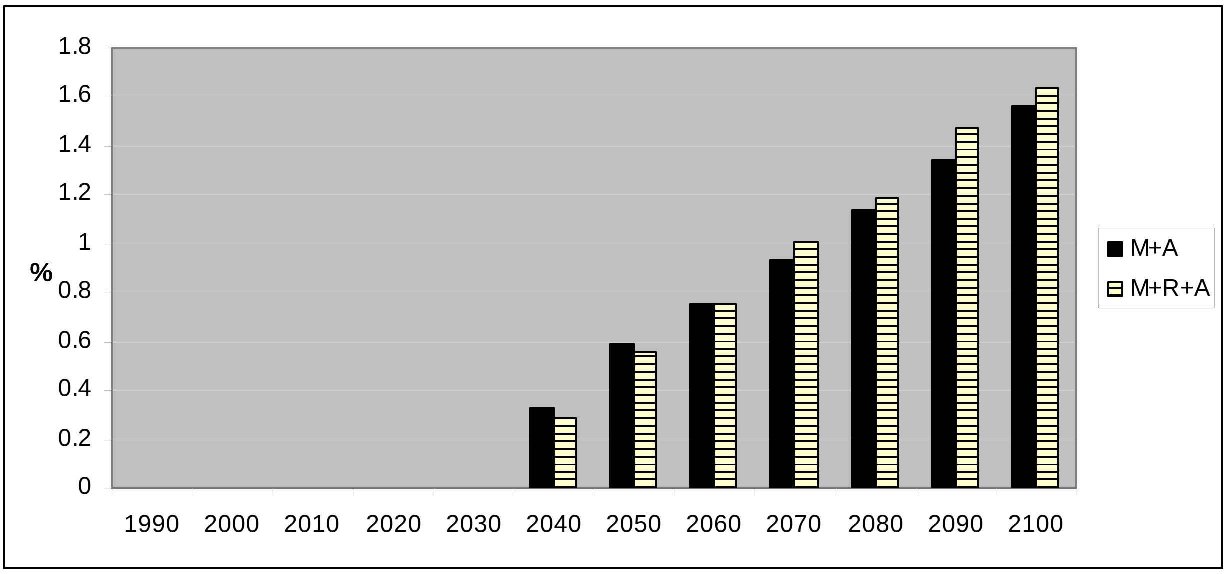
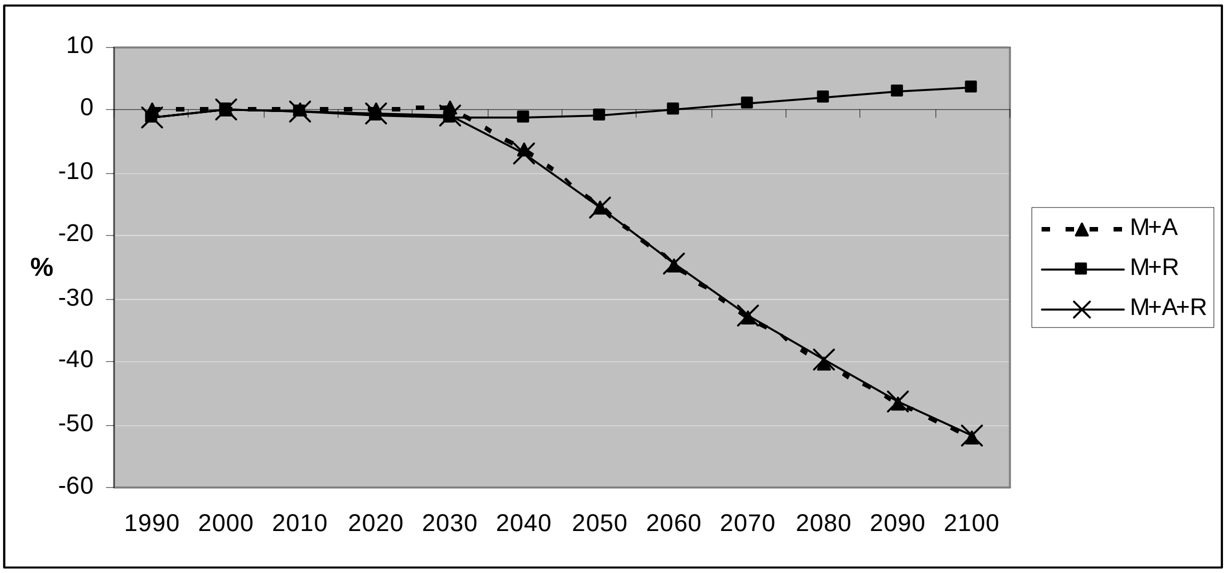


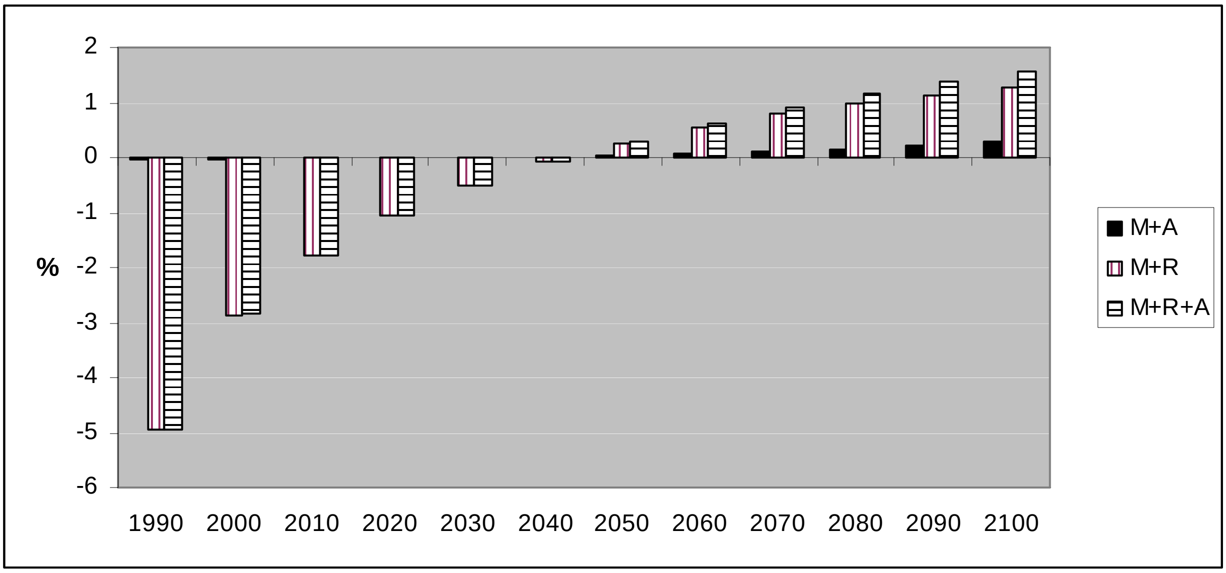
Fig. 5 Discounted environmental damage: % difference w.r.t. mitigation only



These first results highlight that adaptation, mitigation and investment in R&D are competing choices. This is not surprising as resources available to policy makers are finite; accordingly when a new option to fight climate change damages is viable and effectively undertaken a lower amount of resources is available to other strategies. Moreover, adaptation, reducing the negative effect of climate change, also reduces the need to mitigate. However all the three strategies coexist thus they are strategic complements for an optimal management of the climate change problem. This is also highlighted by figure 6 measuring total welfare represented by discounted consumption. Endowing the policy maker with an additional instrument increases the welfare effect of the global strategy.

In 2100 consumption is 0.3%, 1.3%, 1.6% higher when mitigation is coupled respectively with adaptation, R&D, and adaptation with R&D. Note also that initially investment in R&D, as all investment forms, reduces consumption and welfare. Only after 2040 the higher productivity induced by R&D (and the lower penalisation of economic activity induced by adaptation) start to exert their positive effect.

Fig. 6 Discounted consumption: % difference w.r.t. mitigation only



4.2 Cost effectiveness of adaptation and mitigation.

Table 1 compares cost and effectiveness of adaptation and mitigation in the case of exogenous technical progress[3].

Tab. 1: effectiveness and cost of mitigation and adaptation (M+A case)

	Effectiveness of Policies: % Reduction in Discounted Environmental Damage r.t. No Policy					(Discounted) Costs of policies					
	Total	Due to Mitigation	Due to Adaptation	Mitig. % on Total Reduction	Adapt. % on Total Reduction	Total (trillions US$ 1990)	Total Cost as % of GDP	Abat. Costs (billions US$ 1990)	Adapt. Stock (trillions US$ 1990)	Mitig. % on Total Cost	Adapt. % on Total Cost
2020	-0.42	-0.42	0.00	100.00	0.00	0.01	0.008	6.54	0.00	100.00	0.00
2030	-1.13	-1.13	0.00	100.00	0.00	0.01	0.007	7.55	0.00	100.00	0.00
2040	-8.68	-1.84	-6.84	21.17	78.83	0.12	0.10	8.25	0.11	7.10	92.90
2050	-18.76	-2.42	-16.33	12.92	87.08	0.30	0.22	8.72	0.29	2.90	97.10
2060	-28.16	-2.84	-25.32	10.10	89.90	0.51	0.35	9.01	0.50	1.75	98.25
2070	-36.55	-3.11	-33.44	8.52	91.48	0.75	0.47	9.17	0.74	1.22	98.78
2080	-43.84	-3.25	-40.59	7.42	92.58	1.01	0.60	9.22	1.00	0.91	99.09
2090	-50.08	-3.30	-46.78	6.58	93.42	1.28	0.71	9.25	1.27	0.72	99.28
2100	-55.39	-3.25	-52.13	5.88	94.12	1.54	0.83	9.26	1.53	0.60	99.40

According to the model specification, in 2100 it is optimal to allocate a total budget of 1.54 US trillion $ equalling the 0.83% of world discounted GDP to reduce environmental damage by the -55% respect to a situation in which no policy is undertaken.

The role of adaptation and mitigation is very different. On the benefit side (left hand side of table 1), in 2100 adaptation contributes the 94% to damage reduction while mitigation the 6%.

On the cost side (right hand side of the table) in 2100 the total discounted mitigation cost amounts to 9.26 billions of US$ (only the 0.6% of total costs), while total discounted capital immobilised in adaptation amounts to 1530 billions US$ (the 99.4% of total).

These shares result from the functional specification and model parameterisation chosen. Mitigation costs are indeed exponential and rapidly increasing already above a 10% abatement level.

Just to give a numerical indication, while a 6% abatement costs 9 billions $, 2112 billions $ are required for a 50% abatement. In addition effectiveness is also different among strategies: a 50% abatement reduces damages roughly the 30% while a lower expenditure on adaptation (the 1530

[3] To save space, the case with endogenous technical progress, qualitatively similar, is omitted.

billions) reduces damages the 52%. Thus for instance moving 10 billions $ from adaptation to mitigation (in table 4, 2100 row - 9th and 10th columns) which nearly doubles resources devoted to mitigation (from 9 to 19 billions $) and leaves nearly unchanged those allocated to adaptation (from 1.53 to 1.52 trillions $), will allow only a limited increase in abatement and a decrease in damage not compensated by the lower damage reduction on the adaptation side.

What really matters here is the performance of the two strategies at the margin that at the optimum coincide.

4.3. The timing of adaptation and mitigation

Table 1 also highlights a prevalence of mitigation in the first simulation years and of adaptation in the last. While it is not convenient to adapt when climate change damage is very low, this is not so for abatement.

This behaviour is the result of three specific facts highlighted by the modelling exercise.

Mitigation, operating on the *causes* of climate change is constrained by climatic inertia thus it has to be undertaken well in advance to contrast the damage when it eventually materialises. Adaptation on the contrary obeys to socio-economic inertias which are often “smaller” (see on this also Wilbanks, 2005; Klein *et al.*, 2003; Fussel and Klein, 2006) , positive effects can be grasped sooner and thus can be put into force “later”.

Also the time profile of environmental damage determines the observed behaviour: adaptation is shifted forward as damages are low initially and appreciable just in the future.

The results can be explained also under the efficiency ground. Adaptation is an investment, accordingly a unit of investment diverted from capital accumulation to adaptation at time t entails a cost equal to the stream of lost production from t to the end of the simulation period[4]. On the contrary mitigation at time t reduces production at time t only. Initially both capital and damage stocks are low, accordingly the marginal cost of reducing the first is high and the marginal benefit of reducing the second is low. Adaptation in these first phases it is thus not convenient. Mitigation, which does not act on capital stock, but on production, is initially “cheaper” and preferred. In latter phases both capital stock and damage stock increase, and the situation reverses: reducing capital stock has a low marginal cost and reducing damage stock has high benefits. Now adaptation that reduces capital stock is “cheaper” respect to mitigation that reduces output.

4.4. Elasticity

To further investigate the relationship between mitigation and adaptation, the model has been used to estimate numerically the "cross elasticity" of the two strategies.

This has been done according to the following procedure. Firstly, the model has been run to find the optimal path for abatement and adaptation investment. Secondly, (in turn) one of the two control variables has been exogenously moved from its optimal level by a given percentage, the model has been re-run and the new level of the variable left free to vary has been computed. Thirdly, its percentage variation respect to the previous simulation has been calculated. Finally, the ratio between the percentage changes of mitigation and adaptation has been used as an indication of the elasticity of substitution between the two choices[5]. These values are reported in table 2.

Tab.2: cross elasticity of mitigation and adaptation

	M+A		M+A+R	
	Adaptation elasticity to mitigation (1)	Mitigation elasticity to adaptation (2)	Adaptation elasticity to mitigation (1)	Mitigation elasticity to adaptation (2)
1990	Na	0.00	Na	0.00
2000	Na	-0.10	Na	-0.12
2010	Na	-0.14	Na	-0.19
2020	Na	-0.22	Na	-0.29
2030	-0.08	-0.25	-0.09	-0.36
2040	-0.04	-0.38	-0.03	-0.40
2050	-0.06	-0.38	-0.06	-0.45
2060	-0.04	-0.32	-0.04	-0.47
2070	-0.03	-0.45	-0.03	-0.60
2080	-0.03	-0.43	-0.04	-0.82
2090	-0.03	-0.73	-0.01	-0.84

(1) Calculated as: % change in adaptation investment when abatement is increased the 10% from optimum over 10%

(2) Calculated as: % change of abatement when investment in adaptation is increased the 10% from optimum over 10%.

As shown by columns 2 and 4 of table 2, the elasticity of adaptation to mitigation ranges from –0.09 to –0.01. This means that say a 10% increase in abatement would reduce the optimal investment in adaptation by a small 0.9% - 0.1%. The elasticity of mitigation to adaptation is roughly ten times higher ranging from - 0.8 to - 0.1.

[4] Adaptation is represented as an investment not adding to capital stock formation, but to damage reduction. In fact, adaptation affects capital formation albeit indirectly either negatively, crowding out traditional investment, or positively through lower damage and thus higher net present output Y(n,t) (see eq. (2)) and resources available to it.

[5] To check robustness of findings, this procedure has been replicated imposing different percentage increases to both control variables. The values of cross elasticity resulted stable thus only results for a 10% increase are shown. Extended results are available from the author on request.

Mitigation thus appears more responsive to adaptation than *vice versa*, even though in a "rigid" context. This is consistent with what previously shown: (optimal) mitigation has a lower effectiveness especially on near-term climatic damage therefore it does little to decrease the need to adapt. On the contrary, adaptation lowers considerably that damage and thus induces optimally a more appreciable decrease in abatement effort.

Note also that the elasticity of mitigation to adaptation is lower initially and increases with time. This confirms the intuition that optimal mitigation has to start in earlier phases even in the presence of adaptation and that initially it is rather insensitive to it.

What said has important policy implications. Firstly, the possibility to adapt does not eliminate the need to mitigate: mitigation and adaptation remain strategic complements. Secondly, mitigation does not have to be postponed for instance with the justification of waiting for verifying adaptation results. It is even more so considering the quite low elasticity of mitigation to adaptation in the first decades: an eventual increase in adaptation only marginally influence initial mitigation effort. At the same time the exercise shows clearly that, when damages materialise, adaptation has to start. In the model this happens after 2040, but today's world is already experiencing climate-change damages, thus this should urge policymakers for the immediate implementation of adaptation plans. Finally, economic inertia, albeit lower than the environmental one, can be relevant. In these cases also adaptation needs to be implemented with some anticipation.

5 Sensitivity Analysis

An ample sensitivity analysis has been performed testing results' robustness respect to different model parameterisations. Below are reported the outcomes of the sensitivity test over different levels of climate change damage and the discount rate[6].

5.1 Climate change damage

In a first sensitivity test environmental damages are increased (doubled and tripled).

As one could expect, both mitigation and adaptation increase (fig. 7 and 8), however mitigation tends to recover the original values as time passes. This depends on the interactions with adaptation. Higher damages not only foster adaptation, but also tend to anticipate it (one and two periods respectively); the result is to reduce the need to abate especially in the last periods. On the contrary,

[6] Due to space constraints, sensitivity tests over abatement costs and adaptation effectiveness are not reported. They confirm either the substitutability among mitigation and adaptation or the higher reaction of mitigation to adaptation than vice versa. In addition, they point out that in a wide range of parameter values mitigation and adaptation remain

R&D remains basically unchanged (fig. 9). The intuition here is that the two effects of R&D, one beneficial the other detrimental for the environment, almost balance. Accordingly, doubling or tripling environmental damage tend to replicate the optimal R&D investment of the base case.

Fig. 7 Abatement rates: sensitivity analysis over climate-change damage

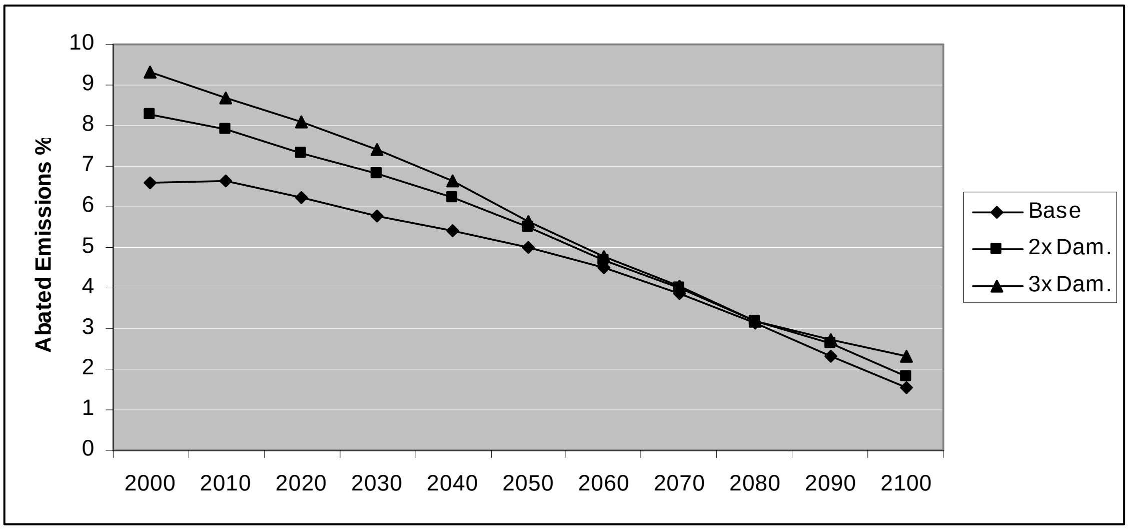
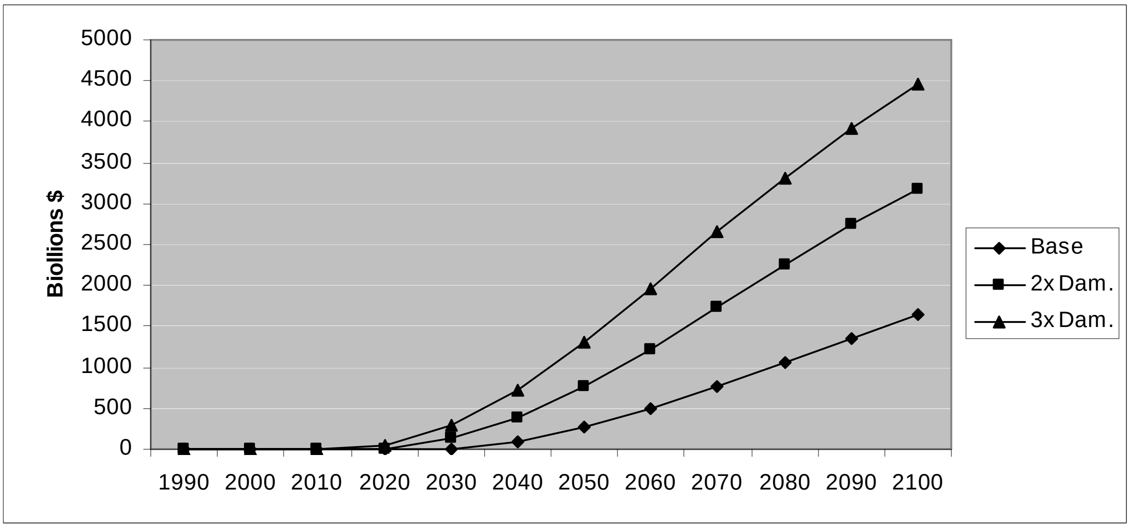
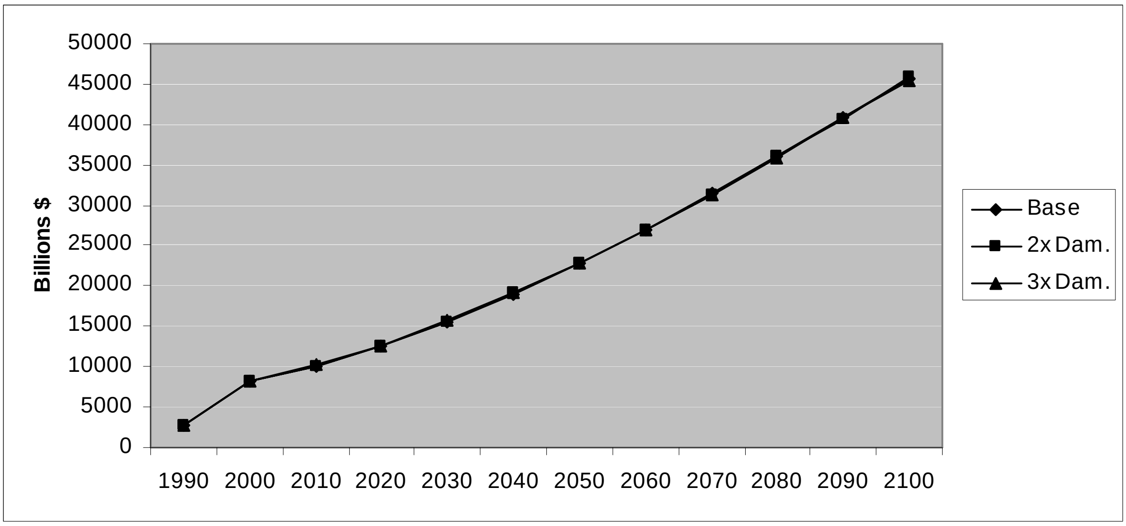


Fig. 8 Stock of defensive capital: sensitivity analysis over climate-change damage



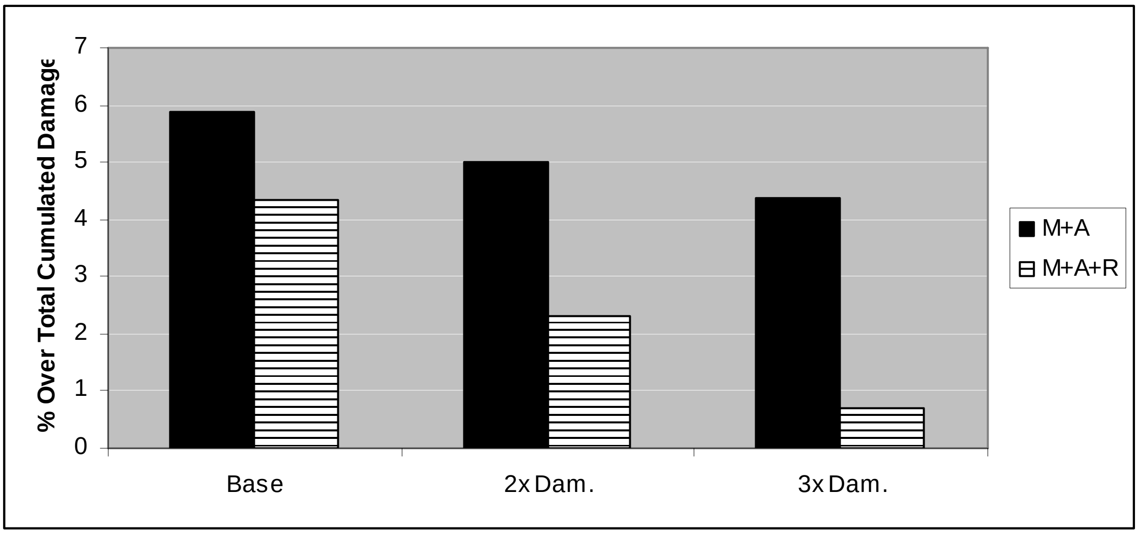
strategic complements: the two are always used in combination. Complete results are available from the author upon request.

Fig. 9 Stock of R&D: sensitivity analysis over climate-change damage



Another interesting result is that increasing environmental damage, the relative contribution to damage reduction of mitigation respect to adaptation decreases (fig. 10). This shift occurs because when damages both materialises and become relevant earlier, adaptation which is more suited than mitigation to cope with near-term damages, is preferred. This effect is stronger in and endogenous technical change world when investment in R&D increases damages.

Fig. 10 Percent share of mitigation in total damage reduction: sensitivity analysis over climate-change damage



5.2 Discount rate

Climate change damages are low initially and high in the future, thus the perception of time expressed by the discount rate is likely to play an important role.

Fig. 11, 12 and 13 respectively demonstrate, as expected, that a decrease in the discount rate, reflecting an increase in the planner's preference for the future, increases mitigation, adaptation and R&D efforts. Moreover adaptation investment is anticipated.

Fig. 11 Mitigation: sensitivity analysis over the discount rate (M+A+R case)

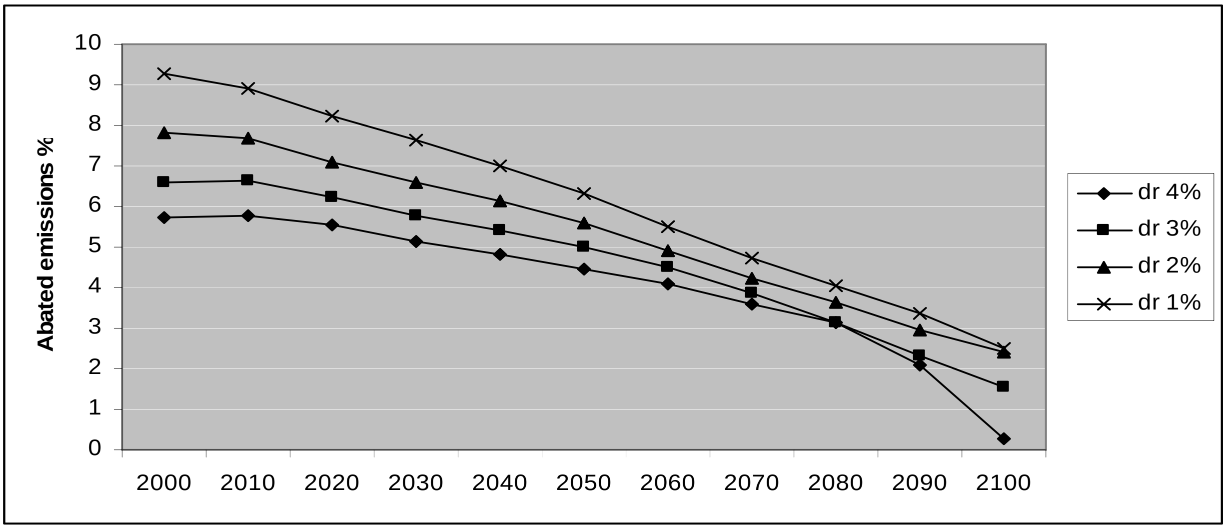


Fig. 12 Stock of defensive capital: sensitivity analysis over the discount rate (M+A+R case)

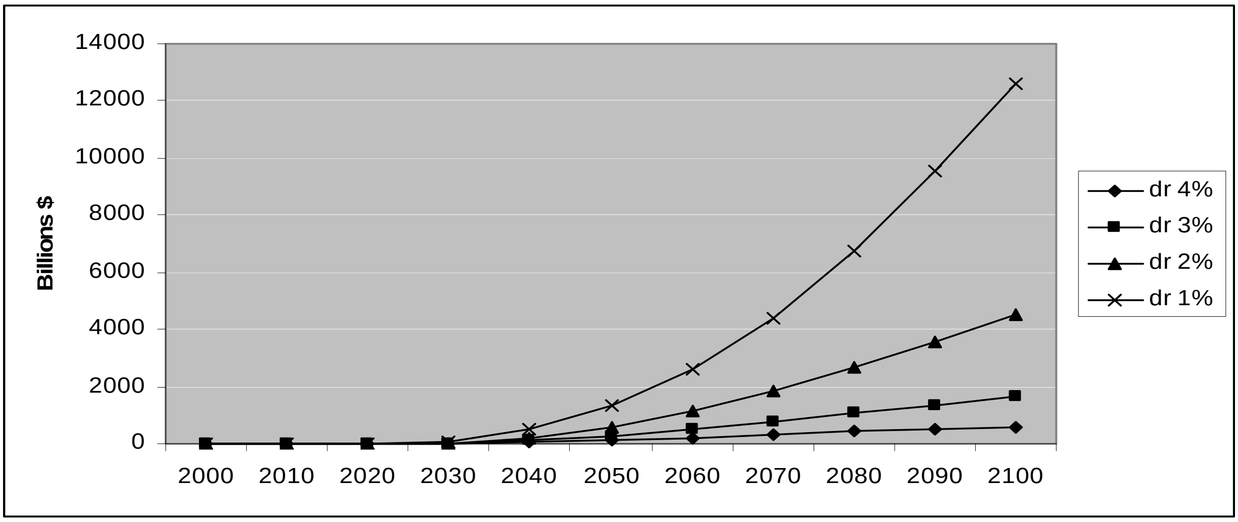
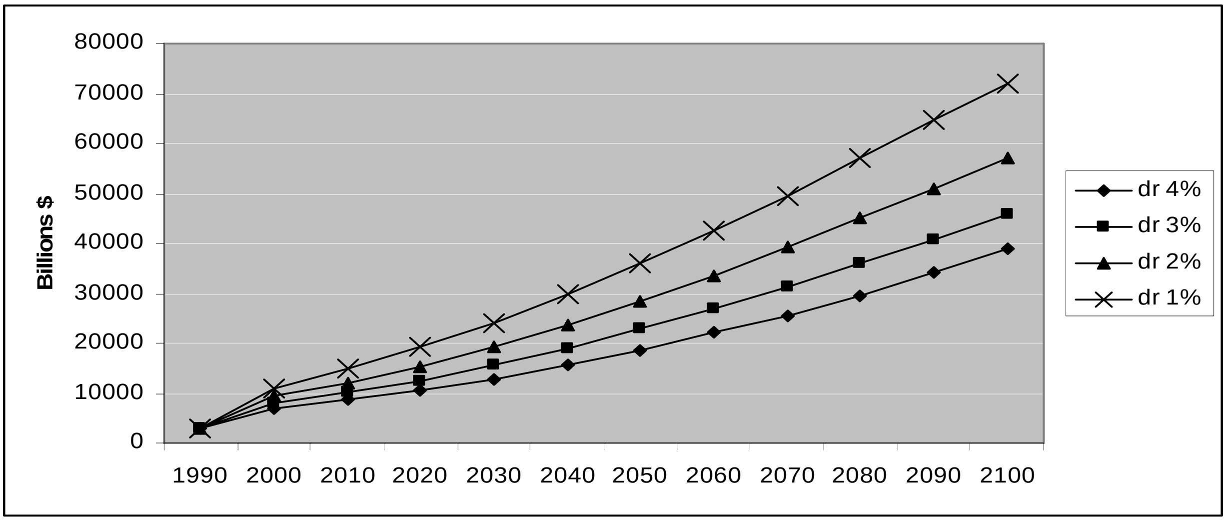


Fig. 13 Stock of R&D: sensitivity analysis over the discount rate (M+A+R case)



More interesting is to verify which strategy is utilised more “intensively” in relative terms. In a world where R&D cannot be chosen by the planner, the strategy increasing more its relative contribution to climate-change damage reduction is mitigation (fig. 14). Mitigation is subjected to a longer-term inertia respect to adaptation, but as the discount rate is progressively reduced, the “intertemporal advantage” of adaptation respect to mitigation lowers and the policy portfolio is re-equilibrated in favour of mitigation.

A nice result is that when R&D is a decision variable, the situation reverses (fig. 15). A lower discount rate increases R&D investment either to the purpose of reducing future damage via the positive environmental effect of decarbonising output or to the purpose of increasing future output via the positive effect on production. As shown previously, the second effect prevails inducing more emissions and a higher and anticipated damage. To contrast this, adaptation is relatively preferred.

These outcomes suggest another policy implication: when future damages are uncertain, assuming that uncertainty is biased toward higher than lower damages or when the policy maker adopts a low discount rate, efficiency suggests to increasing mitigation effort respect to adaptation.

Fig. 14 Percent share of mitigation in total damage reduction: sensitivity analysis over the discount rate (M+A case)

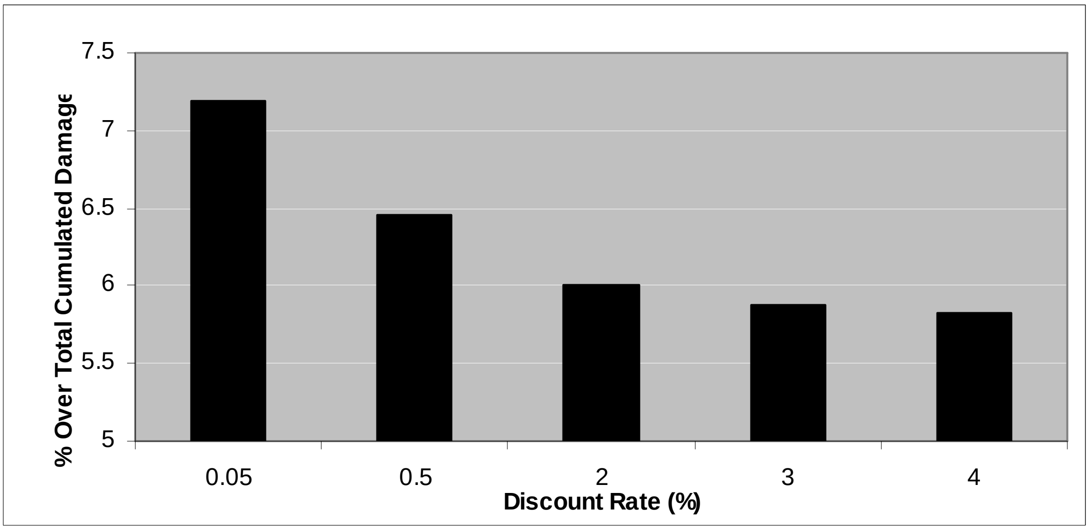
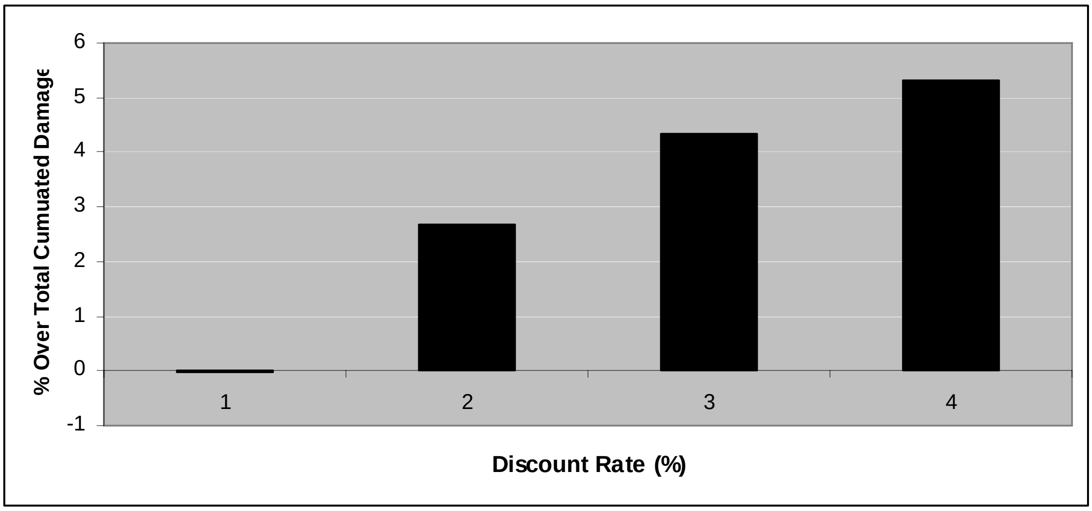


Fig. 15 Percent share of mitigation in total damage reduction: sensitivity analysis over the discount rate (M+A+R case)



6. Summary and Conclusions

This paper proposes an empirical modelling framework to analyse the relationships existing between mitigation, adaptation and investment in technological progress bringing both a positive productivity effect and a decarbonisation of the production system, in the context of climate-change policy.

A first important finding confirms that all these three options are strategic complements as each of them constitute one part of the answer to the problem. This result is robust to a wide range of model parameterisations thus shows that cost effectiveness imposes a mix of policies even though one of them should result particularly effective or cheap.

Secondly, the structural differences between adaptation, investment in R&D and mitigation have been highlighted. Under the benefit side, the first two are constrained by a “shorter” economic inertia, while the other by the “longer” environmental inertia. On the cost side adaptation and investment in R&D penalise capital accumulation in the long-term, while mitigation affects present output only. These facts define the optimal policy mix requiring to anticipating mitigation action (which starts in 2010) and waiting to adapt until damages are substantial (which occurs since 2040). As a main consequence, initially (until 2040 in the exercise) only mitigation contributes to damage reduction while adaptation prevails afterward. This is the main qualitative difference respect to De Bruin et al. (2007) which is driven by this study’s explicit modelling of adaptation as a stock variable. In addition some insights about the responsiveness of one strategy to the other have been provided. Cross elasticity is always lower than one, but mitigation is roughly ten times more responsive to adaptation than *vice versa*. Mitigation has indeed a lower effectiveness especially on near-term climatic damage therefore it does little to decrease the need to adapt. On the contrary, adaptation lowers considerably that damage and thus induces a more appreciable decrease in abatement effort. This results is also found by De Bruin et al. (2007) and echoes the finding of Tol (2007) in the context of sea-level rise.

The third message of the exercise is that adaptation can offer a fundamental contribution to damage reduction either in absolute term or considering the rapidity through which adaptation benefits can be grasped. These two characteristics make adaptation an important policy option that asks to be necessarily included in any policy or scientific analysis concerning climate change. However this requires to invest massively on adaptation and to plan it with some advance anyway as economic inertia, albeit weaker than the environmental one, has to be taken into account.

Finally sensitivity analyses show that each time future damages increase, cost effectiveness of mitigation is found to increase respect to adaptation; the opposite occurs when (sufficiently) near-term *and* future damage is increased. A policy implication is that if there are evidences that future climate damages could be higher than expected, even without certainty, this should strengthen mitigation effort with regard to adaptation. The same conclusion applies should policy decision making decide to use lower discount rates.

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Mathematical appendix

Model equations: endogenous technical change and adaptation

$$\max_{\{C(n,t)\}} \sum_{n=1}^{N} \sum_{t=1}^{T} \phi(n) \left[(1+\rho)^{-(t-1)} L(n,t) \log \left(\frac{C(n,t)}{L(n,t)} \right) \right] \qquad \text{(A1)}$$

$$K(n,t+1) = (1-\delta_K) K(n,t) + I(n,t) \qquad \text{(A2)}$$

$$CC(t+1) = \beta \sum_{n=1}^{N} E(n,t+1) + (1-\delta_{CC}) CC(t) \qquad \text{(A3)}$$

$$SAD(n,t+1) = (1-\delta_A) SAD(n,t) + IA(n,t) \qquad \text{(A4)}$$

$$K_R(n,t+1) = R\&D(n,t) + (1-\delta_R) K_R(n,t) \qquad \text{(A5)}$$

$$Q(n,t) = A(n,t) K_R(n,t)^{\beta_n^R} [L(n,t)^{\gamma} K(n,t)^{1-\gamma}] \qquad \text{(A6)}$$

$$Y(n,t) = C(n,t) + I(n,t) + IA(n,t) + R\&D(n,t) \qquad \text{(A7)}$$

$$Y(n,t) = \Omega(n,t) Q(n,t) \qquad \text{(A8)}$$

$$\Omega_1(n,t) = \frac{\left(1 - b_{1,n} \mu(n,t)^{b_2}\right)}{\left(1 + \theta_1 \cdot \frac{1}{\exp(SAD(n,t))} \cdot \left(T(t)/2,5\right)^{\theta_2}\right)} \qquad \text{(A9)}$$

$$E(n,t) = \sigma(n,t)[1-\mu(n,t)]Q(n,t) \qquad \text{(A10)}$$

$$\sigma(n,t) = [\sigma(n) + \chi(n) \exp(-\alpha(n) K_R(n,t)] \qquad \text{(A11)}$$

$$F(t) = \eta \log[CC(t)/CC(0)]/\log(2) + O(t) \qquad \text{(A12)}$$

$$T(t+1) = T(t) + \left\{ \tau_1 \left[F(t+1) - \lambda T(t) \right] - \tau_2 \left[T(t) - T_{OC}(t) \right] \right\} / \tau_3 \qquad \text{(A13)}$$

$$T_{OC}(t+1) = T_{OC}(t) + \left[T(t) - T_{OC}(t) \right] / \tau_4 \qquad \text{(A14)}$$

Model equations: exogenous technical change and adaptation

Equation (A11) is suppressed and $\sigma(n,t)$ is replaced by an exogenous trend.

Equations (A6) and (A7) are replaced by the following:

$$Q(n,t) = A(n,t)[L(n,t)^{\gamma} K(n,t)^{1-\gamma}] \qquad \text{(A6b)}$$

$$Y(n,t) = C(n,t) + I(n,t) + IA(n,t) \qquad \text{(A7b)}$$

Variable and parameter list:

ρ = discount factor

L = population

C = consumption

K = capital

I = investment

CC = carbon concentration

E = emissions

SAD = stock of adaptation

IA = investment in adaptation

K_R = stock of knowledge

$R\&D$ = investment in research and development

Y = potential output

Q = net output

A = exogenous component of technical change

μ = abatement rate (>=0, <=1)

F = radiative forcing

O = exogenous component of radiative forcing

T = atmospheric temperature

T_{OC} = oceanic temperature

δ_K, δ_{CC}, δ_A, δ_R = depreciations/decays rates

b_1, b_2 = abatement cost parameters

θ_1, θ_2 = environmental damage parameters

β, η, τ_1, τ_2, τ_3, τ_4 = climatic parameters

σ, χ, α = technical change parameters; ϕ = utility weights