

**Adaptation and Mitigation to Global Climate Change:
Conflicting Strategies? Insights from an Empirical Integrated
Assessment Exercise**

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Abstract

This work develops a framework for the analysis at the macro-level of the relationship between adaptation and mitigation policies. A numerical Ramsey growth model with stock pollution and emission abatement is enriched with investment in R&D and investment in adaptation activities. Various simulations are performed to identify: the utility maximizing balance between adaptation cost and benefits, the optimal mix between adaptation, mitigation and investment in R&D, the reactions of optimal path for each control variable to changes in key parameters and the final implication for environmental quality and welfare. The major conclusion of this research is that adaptation, mitigation and R&D are strategic complements as all are a part of the solution of the climate change problem. This outcome is robust to different model parameterization. Also a measure of this complementarity is given. Moreover it is shown that it is intertemporally optimal to anticipate mitigation effort and postpone adaptation intervention.

1. Introduction and Background.

Energy from the Sun drives the Earth's weather and climate. The atmosphere *and* the Sun heat the Earth's surface; in turn, the Earth radiates this energy back into space. The atmosphere, absorbing some of the outgoing energy, retains heat. This is the so-called "greenhouse effect" and without it temperatures would be approximately 30 °C lower than they are now and life as known today would not be possible.

Global Warming is the name given to an *expected* increase in the magnitude of the greenhouse effect, whereby the surface of the Earth will almost inevitably become hotter than it is now.

However, problems arise when human activities, mainly the use of fossil fuels (coal, oil, natural gas and wood) and changes in the land cover, altering the chemical composition of the atmosphere through the build up of greenhouse gases - primarily carbon dioxide, methane, and nitrous oxide - accelerate "*excessively*" this natural process.

The emphasis on the word *excessively* is crucial. The heat-trapping property of these gases is undisputed: warming due to changes in atmospheric composition driven in particular by the increase of CO₂ concentration, partly provoked by human activity, was assessed by Arrhenius already in 1896, then followed by the studies of Chamberlin (1897, 1899) and Ekholm (1901). But only in 1990, the first report of the IPCC - even though highlighting prudentially the still great uncertainty surrounding the whole matter and generally avoiding catastrophic conclusions - stated *with certainty* that human activity is increasing the concentrations of atmospheric greenhouse gases and that these increases will serve to intensify the natural greenhouse effect, resulting in an increased warming of the Earth's surface with the *potential* to harm societies and ecosystems.

Successively to the First Assessment Report, a great deal of effort has been devoted by the scientific community to determine the magnitude and the consequences of this phenomenon and to devise proper policies to cope with it. Because of the recognised role of anthropogenic influence on climate change, the first interventions examined were the so-called mitigation strategies: namely policies aimed to the reduction of greenhouse gases emissions and concentration in the atmosphere.

This responded to criteria of reasonability and precaution, but also reflected what was in the meanwhile happening in the policy arena. Indeed, in December 1990, the UN General Assembly approved the start of treaty negotiation for climate and the environment and in 1992 the UN Framework Convention on Climate Change was signed by 154 states (plus the EC) at Rio de

Janeiro. The final task of the Convention was the “stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved with a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner”¹. Both developed and developing countries accepted a number of general commitments, in particular industrialised countries decided to undertake mitigation policies to reduce their GHG emissions to 1990 levels by the year 2000.

As a consequence the 1995 IPCC Second Assessment Report, in principle containing the best available knowledge on physical and socio-economic aspects of climate change, was almost entirely dedicated to mitigation options. In particular the “Contribution of Working Group III” proposed a deep socio-economic analysis of costs and benefits of such policies.

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. Past and present emissions were estimated to have already committed the earth to at least some climate change in the 21st century. 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 Kyoto Protocol signed in 1997, posing for the first time 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 and basically switched ten years in the future (in the so-called “first commitment period” 2008 -2012) the reduction effort. Moreover the negotiation rounds after Kyoto that should have bridged parties from the signature of the Treaty - representing a mere general agreement - to its ratification - i.e. the effective come into force - saw the defection of important countries like the USA and Australia and long-staggering positions of others like Russia’s. Presently with Russia’s ratification the Kyoto Protocol can become effective, but still there are strong pressures for the renegotiation confirming the difficulty to design and apply even mild mitigation strategies under the environmental viewpoint.

¹ Other agreements adopted at Rio were the Rio Declaration, Agenda 21, The Convention on Biological Diversity and Forest Principles.

These two circumstances spurred the research of alternative responses to the challenges posed by climate change, in particular toward those strategies apt to alleviating the damage once experienced via proper modifications of the impacted socio-economic-environmental systems.

All this is reflected in the 2001 IPCC Third Assessment Reports (TAR). The Contribution of Working Group II to the TAR released with the title: “Impacts, Adaptation and Vulnerability” focussed on how global warming will affect the various regions of the planet, emphasising impacts and socio-economic and environmental vulnerabilities. Moreover it explicitly recognised the role of adaptation to which is devoted chapter 18. The main conclusions are that [p. 879]: “...Adaptation to climate change has the potential to substantively reduce many of the adverse impacts of climate change and enhance beneficial impacts - though neither without cost nor without leaving residual damages...” 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”.

Presently, the research on adaptation tries to reduce the veil of ignorance surrounding this strategy. 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 can adaptation be harmonised with other strategies, first in line, mitigation? In particular are mitigation and adaptation complement or substitute? What is the optimal 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 growth model properly modified. Trade-off and complementarity of the two strategies are highlighted offering some interesting indications about their optimal mix. This exercise and its conclusions are based on quantitative results. Even though the data are consistent with the available knowledge, the quantitative assessment has to be considered just a base to get the qualitative insights. The collection of quantitative information on cost and benefit of adaptation is indeed still too preliminary to offer a solid support to provide reliable figures.

2. Adaptation and planned adaptation more in detail.

In its broader sense, adaptation to climate change can be defined as any adjustment in ecological-social-economic system in response to actual or expected climatic stimuli, impacts or effects (Smit et al. 1999). The adjustment depends only partially on climate-change per se, but mostly on the vulnerability of the impacted system (Jones et al. 2002). As reported in IPCC 2001, p. 21 “Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effect of climate change including climate variability and extremes. [It] is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity and its adaptive capacity”.

Vulnerability can be reduced either by mitigation and adaptation. As said, mitigation basically operates reducing the causes of damage – in particular GHG emissions and concentration in the atmosphere - with the final aim to decrease the probability of adverse conditions for socio-economic and environmental systems. Differently, adaptation reduces the severity of many impacts when/if adverse conditions prevail (Easterling III et al. 2004).

Adaptation is a process taking place through space and time that can take the most diverse forms. Its characterisation depends on different factors. The most important are: the subject of adaptation (who or what adapts), the object of adaptation (what they adapt to), the way in which adaptation takes place (how they adapt). This last aspect includes e.g. what resources are used, when and how they are used and with which results (Wheaton and Maciver, 1999).

The subject of adaptation: Who or what adapts. Adaptation materialises in changes in ecological, social and/or economic systems. These changes can be the result of natural responses and in this case they usually involve organisms or species, or of socio-economic or institutional reactions in which case they are undertaken by individual or collective actors, private or public agents.

The object of adaptation: What they adapt to. In the case of climate change, adaptive responses can be induced either by changes in average conditions or by changes in variability of extreme events. While in the first case the change is slow and usually falls within the “coping range” of systems, in the second case changes are abrupt and outside this coping range (Smit and Pilifosova, 2001).

How adaptation occurs: Modes, resources and results. The existing literature (see e.g. Smit et al. 1999; Klein and Tol, 1997; Fankhauser et al., 1999; IPCC, 2001) proposes several criteria that can

be used to identify the different adaptation processes. Table 1 offers a tentative summary of this classification based upon spatial and temporal aspects, forms and evaluation of performances.

Table 1. Adaptation: Possible criteria for classification

Concept or Attribute	
<i>Purposefulness</i>	Autonomous → Planned
<i>Timing</i>	Anticipatory → Responsive
<i>Temporal Scope</i>	Short term → Long term
<i>Spatial Scope</i>	Localised → Widespread
<i>Function/Effects</i>	Retreat – accommodate – protect – prevent
<i>Form</i>	Structural – legal – institutional
<i>Valuation of Performance</i>	Effectiveness-efficiency-equity-feasibility

Source: Adapted from Smit et al. 1999

For the purpose of this research the most relevant differentiation is that originated by autonomous and planned adaptation. The first can be defined as a natural automatic response to a change, the second responds to a specific planned strategy.

This apparently clear distinction, may originate some confusion when adaptation involves socio-economic agents. Indeed climate change may induce market or welfare effect triggering reactions in private agents without the necessity of a planned strategy designed by a public agency. A typical example is the effect of climate change on crops' productivity. This has both physical effects (changing yields) and economic effects (changing agricultural goods' prices) that can induce farmers to some adaptation (for example changes in the cultivation type or timing). This form of private socio-economic adaptation even though responding to a plan and originated by (rational) economic decisions is considered autonomous (see e.g. Leary 1999, Smith et a. 1996). On the contrary the term planned adaptation is reserved to public interventions by governments or agencies.

The justifications for planned adaptation can be summarised as a matter of scale, timing and co-ordination.

The scale concerns either the amount of information-research or of the investment needed to implement sound adaptation measures. In some cases it can exceed the capacity of a private agent (Consider for example the planning necessary to undertake coastal protection).

The timing refers to the opportunity in many circumstances to adapt in advance rather than in retrofiting: generally private agents tend to adapt “in emergency” while public agents can devise precautionary solutions.

Finally adaptation measures should also be harmonised with existing policies and this requires a full knowledge of the entire socio-economic and institutional picture which is usually more accessible to public than to private bodies.

The different objectives of planned adaptation can be summarised by the following list proposed by Klein and Tol (1997):

- increasing the robustness of infrastructural design and long term investment,
- increasing the flexibility of vulnerable managed system,
- enhancing the adaptability of vulnerable natural systems,
- reversing trends that increase vulnerability (“maladaptation”),
- improving societal awareness and preparedness.

This paper deals with planned adaptation in this sense: the investigation focuses on the decision of a central planner that has to devote resources to undertake an investment program for a long-term adaptation policy.

3. Some data about adaptation.

Quantitative assessments on costs and benefits of adaptation measures are scarce and, when they exist, they generally refer to specific strategies limited in space and time. In general an overall assessment on the role of adaptation is missing.

The reasons are basically two:

First of all the wide heterogeneity of adaptation measures has to be considered. For example, the IPCC TAR (2001) identifies seven major areas in which climate change exerts its impacts: water resources, agriculture and food security, terrestrial and freshwater ecosystems, coastal zones and marine ecosystems, human settlements energy and industry, insurance and other financial services, human health. Adaptive responses vary greatly between each of these impact areas, moreover within each area they are greatly influenced by the vulnerability and adaptive capacity of the

impacted system. Accordingly any adaptive strategy differs from each other and it neither is possible to find adaptive policies universally appropriate nor to draw an organic picture about effectiveness, efficiency, feasibility, costs of adaptation in general.

Secondly, for their own nature, adaptation strategies are often responsive and autonomous; in these cases it is difficult to disentangle their costs and benefits as they are implicitly part of the overall global effect. For instance, this is typically the case of adaptation in the agricultural or in the health sectors: agents' autonomous reactions to the changing environment contribute to produce the final result, but they can hardly be separated from the effect of anticipatory and planned strategies.

Bearing this in mind, tab. 2 provides a survey of cost estimates associated with adaptation. It is adapted from Tol et al. (1998) and enriched with some more recent studies.

Tab. 2: Costs of adaptation strategies, selected result from the literature

Study	Region	M\$	Comment
COASTAL PROTECTION			
<i>Cline (1992)</i>	USA	1200	Annuitised cost of partial protection against a 100 cm. sea level rise
<i>Fankhauser (1995)</i>	USA	160	Annuitised cost of partial protection against a 50 cm. sea level rise
	OECD	448	
	FSU	46	
	Developing Countries	421	
	World	915	
<i>Tol (1995)</i>	North America	1500	Annuitised cost of partial protection against a 100 cm. sea level rise
	OECD	5000	
	EE and FSU	500	
	Developing Countries	4000	
	World	9500	
<i>Bosello et al. (2004a)</i>	USA	5153	Annuitised cost of total protection against a 25 cm. sea level rise
	European Union	11214	
	EE and FSU	23077	
	Japan	7596	
	Oth. Annex 1 countries	71497	
	Net Energy Exporters	36386	
	China and India	11747	
	Rest of the World	38809	
	World	207458	
SPACE HEATING AND COOLING			
<i>Cline (1992)</i>	USA	11200	Extra cost for space cooling, (2.5°C warming)
		1300	Cost savings for space heating same scenario
<i>Fankhauser (1995)</i>	USA	6900	Net increase in energy expenditure, mostly space cooling (2.5°C warming)
	OECD	20490	
	FSU	-682	
	Developing Countries	3257	
	World	23065	
<i>Rosenthal et al. (1995)</i>	USA	-7600	Net decrease in heating and cooling expenditure (2.5°C warming)
RESETTLEMENT AND MIGRATION COSTS			
<i>Cline (1992)</i>	USA	500	Cost to the US of absorbing 100,000 additional immigrants (2.5°C warming)
<i>Fankhauser (1995)</i>	USA	450	Cost of resettlement and foregone earnings (2.5°C warming)
	OECD	2048	
	FSU	153	
	Developing Countries	2126	
	World	4327	
<i>Tol (1995)</i>	North America	1000	Total cost: destination country+country of origin+immigrants (2.5°C warming)
	OECD	2700	
	EE and FSU	500	
	Developing Countries	10700	
	World	13800	
ADJUSTMENT IN AIR AND WATER QUALITY EXPENDITURE			
<i>Cline (1992)</i>	USA	3500	Additional defensive expenditure to meet standards for tropospheric ozone (2.5°C warming)
<i>Titus (1992)</i>	USA	34000	Additional control cost to meet water quality standards (2.5°C warming)
HUMAN HEALTH			

<i>Bosello et al. (2004b)</i>	USA	-33513	Additional health expenditure: malaria, schistosomiasis, dengue, diarrhoea, cardiovascular and respiratory diseases (1°C warming)
	European Union	-41019	
	EE and FSU	-4202	
	Japan	-5313	
	Oth. Annex 1 countries	-6675	
	Net Energy Exporters	29048	
	China and India	-880	
	Rest of the World	50562	
	World	-11990	

Source: adapted from Tol et al. (1998)

As can be seen only adaptation to some impact categories is considered. Other important classes are missing (for example adaptation in the energy or industrial sectors, adaptation strategies in the agricultural sector²). Moreover results are in general very difficult to compare because of the differences in underlying assumptions. Then, when comparisons are possible, differences remain large. Finally costs reported can be considered only rough approximation of the “true” adaptation costs. Consider for example the case of net energy increase for space cooling or the additional health expenditure induced by climate change. These categories of cost are surely only a part of total adaptation cost induced by space warming or changes in health status: to fight space heating for instance better building insulation or higher consumption of fresh food and water should be included; to contrast changes in the diffusion of climate-change related diseases, changes in health expenditure is only a part of the story: shields against vectors, resettlement, prevention policies and change in habits should be considered as well. All this highlights the still great degree of uncertainty underlying these figures and the need of further research.

Anyway, with all the caution of the case, the most striking message of table 2 is that adaptation measures are able to offset more or less the 100% of some categories of climate-change induced damage at a relatively low cost. For example, the annuitised cost of total coastal protection against 25 cm. of sea level rise³ (where total means full protection of coastal areas with a population density higher than 10 inhabitants per sq. Km.) amounts “only” to the 0.7% of world 1997 GDP. The expenditure to offset the effect of 2.5 °C temperature increase inside buildings is estimated to be roughly ten times smaller. At the global level health adaptation cost is negative (basically the decrease in cold stress related diseases more than compensate the increase in heat stress related diseases). But at the regional level health expenditure is the highest: protection against health status worsening induced by 1°C warming amounts to 1% to 3% of regional GDP.

² Many studies on climate change impacts on agriculture do consider farmers’ autonomous adaptation (see e.g.: Adams et al. 1995; 1999a; 1999b). But often neither it is often possible to disentangle the effect of adaptation from the total

Table 3 proposes a tentative summary and comparison of the data. To do this the costs reported in table 2 are rescaled linearly and uniformed to a 0.93 °C common warming scenario estimated for the year 2050⁴.

Table 3: Global adaptation costs for different categories of climate change damage. (0.93°C warming in 2050)

	M. US\$ 1997	% of GDP in 2050	Study
Full Coastal Protection	207458	0.109	(a) From Bosello et al. (2004a)
Space Heating and Cooling	340.38	0.00018	(b) From Fankhauser (1995)
Resettlement and Migration Costs	1609.644	0.000852	(c) From Fankhauser (1995)
	5133.6	0.0027	(d) From Tol (1995)
Health	79611	0.041	(e) From Bosello et al. (2004b)
TOTAL	289019.02	0.148	(a)+(b)+(c)+(e)
TOTAL	292542.98	0.15	(a)+(b)+(d)+(e)

Source: our calculation based on indicated studies

The conclusions reported in table 2 are even reinforced. In 2050, a complete adaptation to the damage implied by the four different climate change consequences listed is roughly equal to the 0.15% of world GDP.

Surely this information gives only a lower bound for adaptation costs, nevertheless it points out that adaptation can represent an important strategy to cope with climate change. It seems particularly effective: it is able to offset if not 100% of damage at least a great part of it and it is particularly cheap.

In the light of this, it becomes interesting to get some indication on the “optimal” level of adaptation. This under two different perspectives: the first is the cost minimising balance between adaptation costs and benefits, the second is the optimal balance between adaptation and other possible strategies like mitigation.

This will be the task of the next sections.

effect nor, when some measures of the benefit of these strategies in alleviating the adverse climatic consequences are provided, information on costs are available.

³ Plausible in 2050, IPCC (2001).

⁴ This forecasted temperature increase derives from Bosello et al. 2004. The data is gotten from the coupling of an economic model with the reduced form Schneider Thompson GCM. The value lies within the spectrum of IPCC estimates predicting for 2050 an increase in temperature ranging from 0.5 to 2.4 °C warming.

4. The Modelling Exercise

4.1. The model

The basic model used for this study is an enriched version of the Nordhaus and Yang (1996)'s RICE96 model. RICE96 is one of the most popular and manageable integrated assessment tools for the study of climate change.

It is basically a Ramsey-Keynes growth model extended to incorporate the interaction between the economic activity and climate. The world is divided into six macro regions (USA, Japan, Europe, China, Former Soviet Union and the Rest of the World). Within each region a central planner chooses the optimal path of fixed investment and rate of abatement to maximise the discounted value of per capita consumption flow of her representative household. The same pure rate of social time preference is used for all regions and is constant throughout time. 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 technology is exogenously determined: a 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 of the model (Buonanno et al. 2000), an 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 affects also the emission-output ratio (the proportionality relationship between emissions and output) 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 CO₂ emission flow - undesired by-product of production activity - in increase of CO₂ concentration on its turn determining radiative forcing and

finally temperature. These passages are governed by the reduced form two-equation Schneider-Thompson climate model. All the parameters are derived through calibration with general circulation models.

4.2. Implementing an adaptation module in RICE96

The full set of equations of the extended version of RICE96 is reported in appendix. Here we focus on the equations describing the adaptation module.

Our choice is to model adaptation as a further form of investment. This is motivated by the fact that here we are concerned with planned adaptation that takes the form of an explicit long-term program decided by a fully rational decision maker. The dynamic of the system is thus enriched by an additional state variable representing the stock of adaptation $SAD(n,t)$ region and time specific. The law of motion for this new stock is:

$$SAD(n,t+1) = (1 - \delta_A)SAD(n,t) + IA(n,t) \quad (1)$$

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:

$$Y(n,t) = \Omega(n,t)Q(n,t) \quad (2)$$

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

with the initial condition:

$$SAD(n,0) = 0. \quad (4)$$

$Q(n,t)$ 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.

Note that 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 following remarks to our specification are in order:

- 1) The model assumes perfect foresight and rational economic agents.
- 2) According to equation (3) climate-change damage is driven only by the temperature level. Other important sources of damage like climate variability, temperature rate of change or irreversibility are not considered. Thus the model deals only with changes in average conditions.
- 3) At this stage of the research 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. Her control variables are four: investment in physical capital, investment in R&D (when this is endogenous), investment in adaptation and abatement.

5. Selected Results

In what follows, results for four different model specifications are presented. At the two extremes we have the case with no adaptation and no endogenous choice on R&D investment (corresponding to the original RICE96 model) offering a sort of benchmark and the case with adaptation and endogenous R&D investment. In between lies the case with no adaptation, but endogenous R&D (corresponding to the improved RICE96 model by Buonanno et al. (2000)) and the case with adaptation, without endogenous R&D.

5.1. The effects of adaptation.

According to our model specifications, *the possibility to invest in adaptation activities induces the central planner to decrease the amount of abatement and the amount of investment in R&D. There is a negative effect on CO2 emissions and temperature which increase. Nevertheless adaptation greatly reduces the negative impact of climate change.*

When adaptation is undertaken, abatement rates are significantly lower (-25% in 2000, -80% in 2100) compared to the case without R&D and adaptation (see fig.1). The stock of knowledge also declines (-5.8% in 2100 see fig. 2). Emissions accordingly increase (peaking to + 11 % and + 22% when investment in R&D is exogenous and endogenous respectively see fig. 3). Notwithstanding lower abatement and higher emissions, adaptation reduces consistently the negative impact induced by climate change on the economic system. Adaptation appears in the long term (fig.4). It starts to be appreciable after 2050 - when damage is reduced the 14% - and booms afterward - when damage is reduced up to the 50% - (see fig. 5). Note here that cases with and without R&D investment are very similar.

Fig. 1

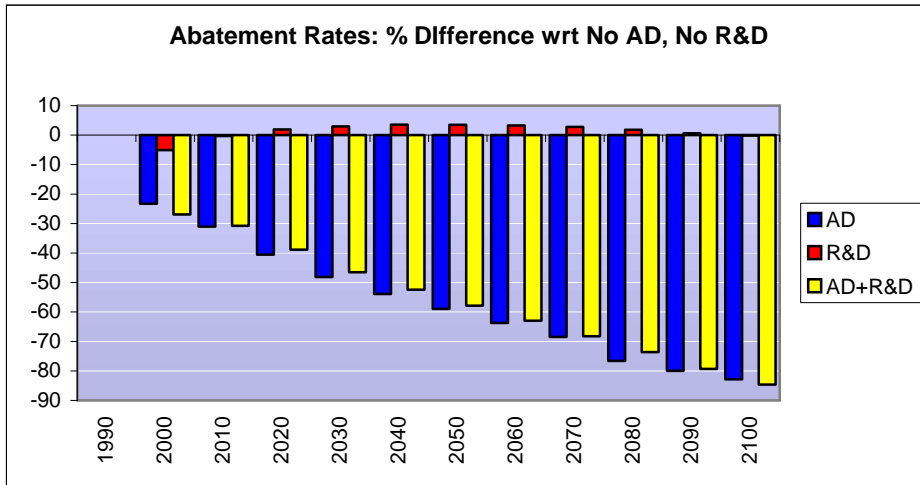


Fig. 2

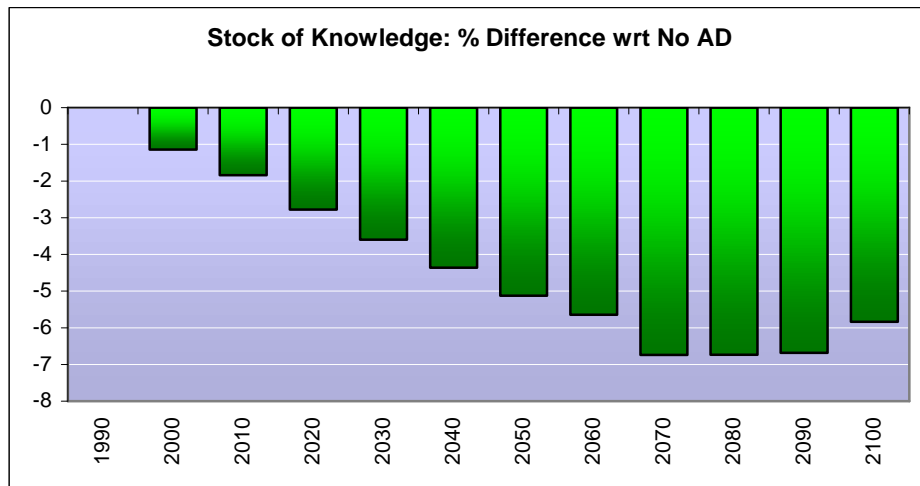


Fig. 3

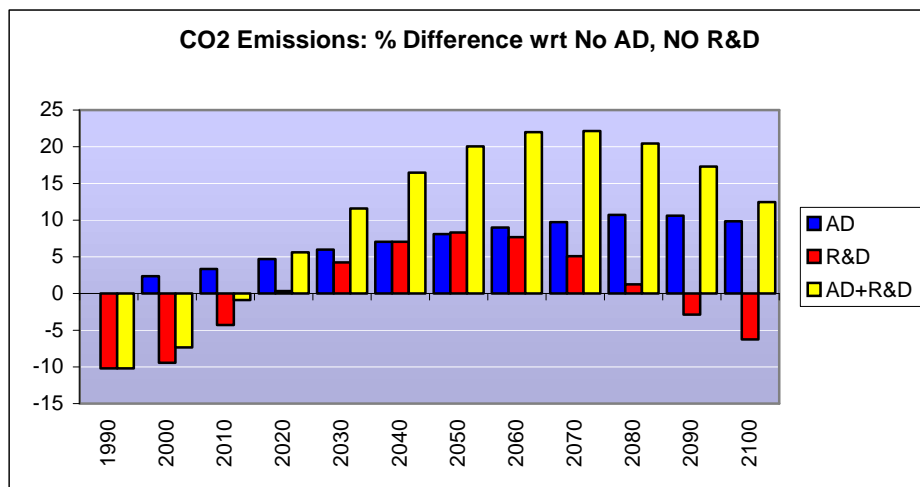


Fig. 4

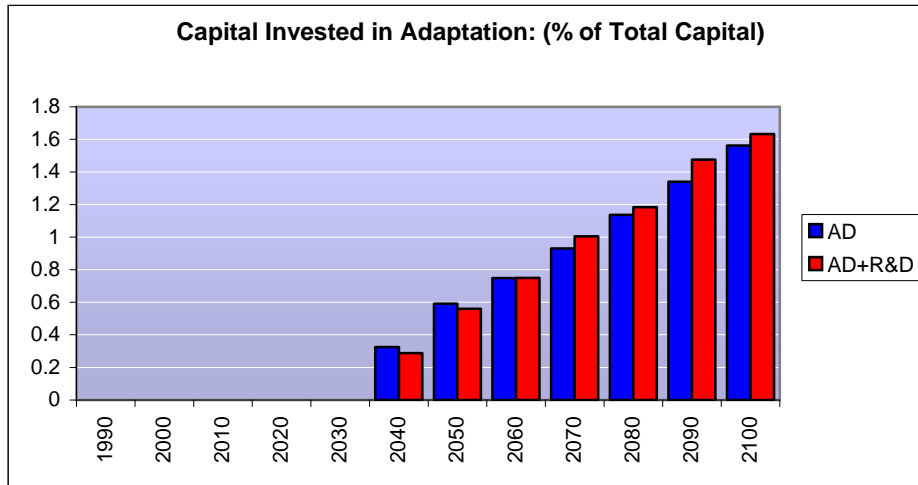
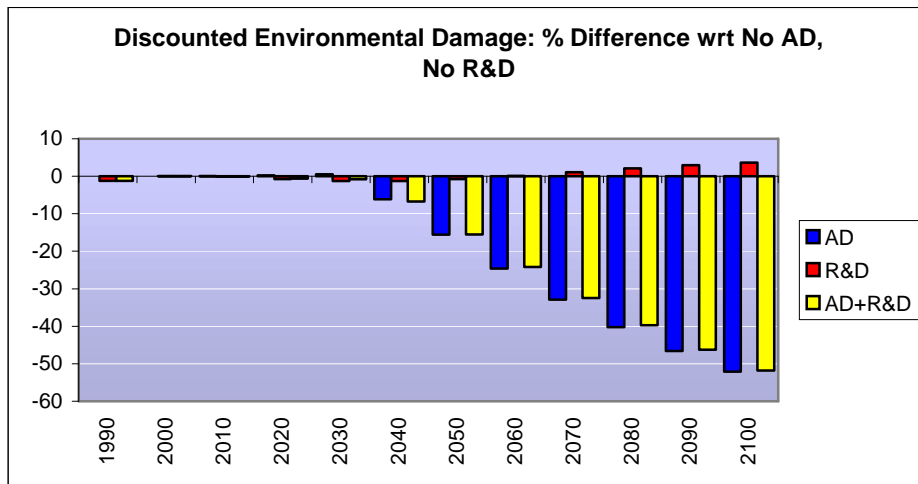


Fig. 5



These results highlight first that: *(Investment in) Adaptation, (abatement) mitigation and (investment in) R&D are competing choices*. This is not surprising: resources are finite; accordingly when a new option to fight climate change damage is viable and effectively undertaken a lower amount of resources is available to other strategies. Moreover adaptation, reducing the negative effect of environmental damage, also reduces the need to mitigate. More interesting is the fact that according to the model *all the three strategies can coexist*. As it is well known, optimality requires that in each period t the marginal cost of each strategy equals the discounted stream of its marginal benefits. At the same time marginal costs should be equalised between strategies. The result points out that no strategy fully dominates one of the other.

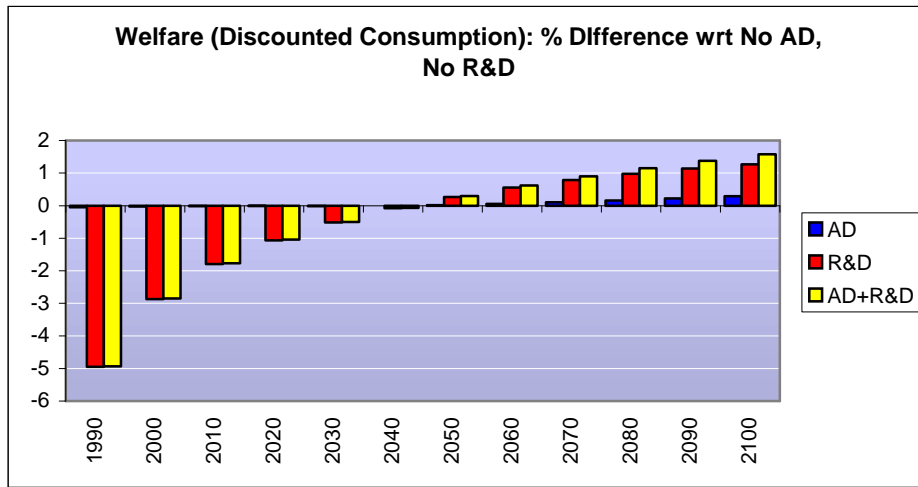
Secondly it also emerges that *full adaptation, i.e. an adaptation investment offsetting the 100% of climate-change damage is not optimal*. In 2100 still the 45% of environmental damage is unabated.

To conclude the section, an indication on welfare - here represented by discounted consumption - is offered. Initially (Fig. 6) the presence of endogenous investment in R&D and adaptation reduces consumption levels respect to the no adaptation exogenous technical progress case. But note that this first decrease in consumption is induced only by the investment in R&D given that no adaptation investment takes place before 2040. After 2040, adaptation and R&D increase consumption. Here the joint effect of the lower penalisation of economic activity induced by adaptation and the higher productivity induced by R&D start to exert their positive effect. In 2100 consumption is 0.3%, 1.3%, 1.6% higher in the cases respectively of adaptation, endogenous R&D, and endogenous R&D with adaptation. As can be expected, endowing the policy maker with an additional tool increases the welfare effect of the global strategy. The welfare is indeed the highest when the two options of investment in R&D and in adaptation can be exploited together. Interestingly the welfare effect of R&D seems to be higher than that of adaptation. This highlights the important role of R&D.

We draw a particular attention also on the well known time trade-off between costs and benefits of climate-change controls. A fact working against climate-change control policies is that costs sustained in the present produce benefits only in the (often far) future. This because policies operating on the *causes* of climate change are unavoidably constrained by climatic inertia and a long time has to pass since a decrease in emissions translates in a decrease in temperature and eventually in damage. This feature is not appealing for a policymaker who should wait a long time (e.g. 50 years in fig. 6) to enjoy some net advantages of a mitigation policy. This is not entirely true in the case of adaptation policies. Fig. 6 for example shows that investments in adaptation undertaken in 2040 start to produce net benefits in 2050, after 10 years only. This result captures the fact that *adaptation, which operates on (alleviating damaging) consequences must obey only to socio-economic inertia⁵ which is usually “smaller” than the climatic one. Thus positive effects can be grasped “sooner”*. Under this perspective the possibility to adapt can increase the favour of climate change policies in decision makers' preferences.

⁵ For example the time needed to build a dike, to change a culture mix or timing, to install air conditioning etc. .

Fig. 6



5.2. On the cost effectiveness of adaptation and mitigation.

Firstly we propose a comparison between adaptation and mitigation contrasting their respective cost and effectiveness.

Tab. 4

EX TP	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

Table 4 does so for some selected years in the case of exogenous technical change⁶.

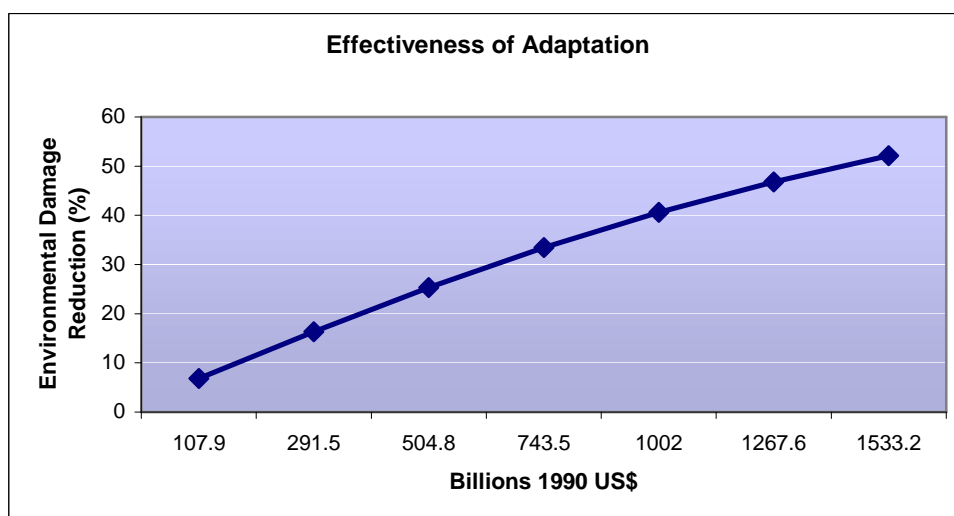
Firstly note the utility maximising cost-benefit ratio of climate-change damage control: according to the model, in 2100 it is optimal to allocate a total amount of 1.54 US Trillion \$ equalling the 0.83% of discounted GDP to reduce environmental damage by a -55% respect to a situation in which no policy is undertaken.

The role of adaptation and mitigation is indeed very different. On the benefit side (left hand side of table 4), 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)⁷.

Figures 7 and 8 put this information together comparing the cost of the two policies with their effectiveness in term of % damage reduction.

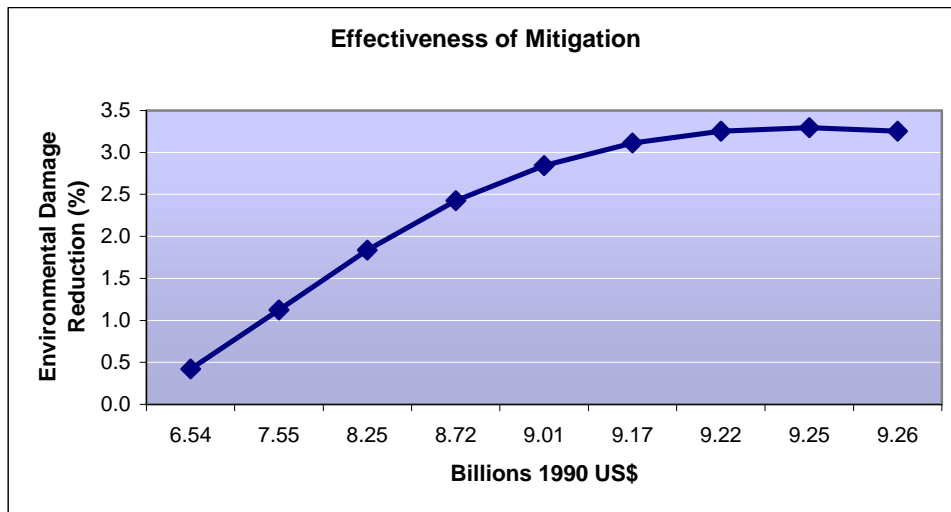
Fig. 7



⁶ This is a technical fact. Only when technical progress is exogenous it is possible to disentangle clearly the contribution to damage reduction due to mitigation. When investment in R&D is considered it exerts its influence on emission and temperature together with mitigation and it becomes impossible to separate the two.

⁷ These figures are purely indicative and based on heroic assumptions. Nevertheless note that adaptation costs are in any case well above the value of 0.15% of GDP offsetting the 100% of four categories of climate change damage reported by the literature that we assumed as the lowest possible bound. For instance in our case in 2100 adaptation offsets the 52% of total damage with a cost of the 0.8% of world GDP.

Fig. 8



It emerges clearly that mitigation is more effective than adaptation. To get an indication of this mismatch consider the slopes of the two curves: this is 0.03 in the case of adaptation and 1.09 in the case of mitigation. Roughly speaking 1 trillion dollars invested in adaptation can reduce environmental damage of the 0.03% while the same amount invested in mitigation of the 1%.

There are precise justifications for such an abundance of resources devoted to adaptation.

The first is the strong non linearity of mitigation (abatement) costs. In fact they are exponential. This property is essential to reproduce a very high cost associated to an abatement level of the 100% which is likely to be an impossible target in a real world. In particular the model - in its present calibration in accordance with the observable evidence - starts to present high and rapidly increasing abatement cost above a 10% abatement level.

The second, even though less determinant, is the difference in benefits entailed by mitigation and adaptation. This discussion is developed in depth in next sections, here we just anticipate that when resources devoted to adaptation and mitigation are comparable in magnitude, adaptation is “more effective” than mitigation in reducing environmental damage.

Just to give some numerical indication, firstly, under the cost side, consider 2100 in table 4 - 9th and 10th columns. Apparently it may seem sensible to move 10 billions \$ from adaptation to mitigation; this would nearly double resources devoted to mitigation (from 9 to 19 billions \$) and leave nearly unchanged those allocated to adaptation (from 1.53 to 1.52 trillions \$). Unluckily, because of the exponential structure of abatement costs these additional resources available for mitigation allow just a small increase in abatement. To give an order of magnitude: if 9 billions \$ allow a 6% abatement, 2112 billions \$ are required for a 50% abatement.

Then under the benefit side: increasing abatement for instance nearly 10 times (from 6% to 50%) costs 2103 billions \$ more and allows a further damage reduction of the 29%, while 1530 billions \$ allocated to adaptation reduce the damage the 52%.

In reality what really matters here is the performance of the two strategies at the margin. At the optimum they must be equal, particularly the additional cost of the two policies responding to an incremental reduction in climate change damage.

To get a rough approximation of this data, in turn the optimal rate of abatement and the optimal rate of investment in adaptation have been slightly increased in two selected years, comparing additional costs and benefits.

Tab. 5

	Mitigation		Adaptation	
	Additional discounted damage reduction wrt optimum (US\$ trillion)	Additional discounted cost wrt optimum (US\$ trillion)	Additional discounted damage reduction wrt optimum (US\$ trillion)	Additional discounted cost wrt optimum (US\$ trillion)
2030	0.076	0.096	0.065	0.101
2100	0.108	0.064	0.126	0.074

As can be seen in table 5 obtaining an additional reduction of discounted environmental damage in 2030 of roughly 0.7 trillion \$ implies an additional cost of roughly 0.1 trillion \$ for both policies. The same happens in 2100: an additional damage reduction of roughly 0.1 trillion \$ costs 0.06 trillion \$ for both⁸.

5.3. A note on timing

Another interesting result highlighted by table 4 is the evident *prevalence of mitigation in the first simulation years and of adaptation in the last*. What emerges here is that it is not convenient to adapt when climate change damage is very low, but rather to abate.

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

⁸ It is not possible here to get a finer information on marginal values. Smaller increments are indeed above the numerical capacity of the model to give differences in the results. This of course limits a lot the precision of the numerical result.

Firstly consider inertias. Apparently mitigation and adaptation are similar: a unit of environmental damage reduced at time t , whether through mitigation or adaptation, produces a stream of benefits over time equal to the avoided damage that that unit would have produced along all the simulation period. But unlike adaptation, mitigation is constrained by a strong inertia thus it has to be undertaken well in advance to contrast the damage when it eventually materialises. Adaptation on the contrary is rapidly effective and thus can be put into force in the “last minute”.

Secondly, reinforcing the argument above, consider the time profile of the environmental damage: it is very low initially and appreciable in the future only. This is a further reason shifting adaptation in the future.

Finally consider costs. 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 period⁹. 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 does exactly this thus in these first phases it is 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.

5.4. Elasticity

Here we offer some figures to shape the relationship between mitigation and adaptation.

This has been done according to the following procedure. Firstly, the model has been run to find the optimal path for abatement and for adaptation investment. Secondly, (in turn) one of the two control variables has been exogenously moved from its optimal level by a given percentage. Thirdly the model has been re-run and the new level of the other variable, left free to vary, has been computed. Finally the percentage variation of the free variable has been calculated. The ratio between the percentage change of mitigation (abatement) and the percentage change of adaptation should give a

⁹ Adaptation is represented as an investment not adding to capital stock formation, but to damage reduction. In reality an indirect effect of adaptation on capital formation is indeed present. A lower damage implies a lower penalisation of net present output $Y(n,t)$ (see eq. (2)) and thus more resources are available for consumption and “traditional” investment.

rough estimate of the elasticity of substitution between the two choices. These values are reported in table 6 and 7 for the case of exogenous and endogenous technical change respectively.

Tab.6

EX . Tech. Change	Adaptation elast. To mitigation			Mitigation elast. to adaptation		
	Ab.-5%	Ab.-10%	Ab.-20%	IA+1%	IA+2%	IA+10%
1990	0.00	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.00	0.00	-0.09	-0.08	-0.10
2010	0.00	0.00	0.00	-0.13	-0.12	-0.14
2020	0.00	0.00	0.00	-0.13	-0.17	-0.22
2030	-0.08	-0.08	-0.08	-0.20	-0.20	-0.25
2040	-0.04	-0.04	-0.04	-0.29	-0.24	-0.38
2050	-0.06	-0.06	-0.06	-0.35	-0.33	-0.38
2060	-0.03	-0.04	-0.03	-0.40	-0.35	-0.32
2070	-0.03	-0.03	-0.04	-0.42	-0.52	-0.45
2080	-0.03	-0.03	-0.04	-0.40	-0.40	-0.43
2090	-0.03	-0.03	-0.03	-0.40	-0.49	-0.73

Tab. 7

EN. Tech. Change	Adaptation elast. To mitigation			Mitigation elast. to adaptation		
	Ab.-5%	Ab.-10%	Ab.-20%	IA+1%	IA+10%	IA+20%
1990	0.00	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.00	0.00	-0.13	-0.12	-0.11
2010	0.00	0.00	0.00	-0.22	-0.19	-0.17
2020	0.00	0.00	0.00	-0.35	-0.29	-0.27
2030	-0.09	-0.09	-0.09	-0.42	-0.36	-0.34
2040	-0.04	-0.03	-0.03	-0.39	-0.40	-0.36
2050	-0.07	-0.06	-0.06	-0.39	-0.45	-0.42
2060	-0.04	-0.04	-0.05	-0.33	-0.47	-0.46
2070	-0.03	-0.03	-0.03	-0.37	-0.60	-0.53
2080	-0.03	-0.04	-0.04	-0.73	-0.82	-0.76
2090	-0.01	-0.01	-0.02	-0.80	-0.84	-0.77

We comment table 6 only as table 7 is qualitatively similar. As shown by the left part of table 6, the elasticity of adaptation to mitigation (computed calculating the % change of investment in adaptation when optimal abatement is decreased the 5%, 10% and 20% - the different percentage reductions have been used to test the robustness of the results-) ranges from -0.08 to -0.03 . This means that say a 10% increase in abatement would reduce the optimal investment in adaptation by a tiny 0.8%-0.3%.

Looking at the right hand side of the table, the elasticity of mitigation to adaptation is higher. Depending on the year, it ranges from -0.08 to -0.5 with a mean of -0.3 . (Here the values are much unstable).

Summarising, *mitigation is more responsive to adaptation than vice versa, even though in a “rigid” context*. This is consistent with what previously shown: (optimal) mitigation lowers only slightly the environmental damage stock which is also the determinant of adaptation (e.g. the reduction in discounted environmental damage due to mitigation in 2100 is “only” the -7% if compared to the no policy case). Therefore mitigation does little to decrease the need to adapt. On the contrary, adaptation does lower considerably environmental damage and thus induces an optimal decrease in abatement effort.

Note also that *the elasticity of mitigation to adaptation increases with time and initially it is quite small*. This seems to confirm the intuition that in earlier phases mitigation is a “preferred” strategy than adaptation as it is influenced only marginally by the latter.

6. Sensitivity Analysis

6.1. Robustness

In this section we concentrate on the parameterisation governing the effectiveness of adaptation in reducing the penalisation of total production induced by climate change and on that determining the cost of abatement activity.

In the first case a multiplier to $SAD(n,t)$ in eq. (3) has been added and then properly changed; in the second it has been sufficient to vary the parameter $b_{1,n}$.

As shown by fig. 8, when the effectiveness of capital invested in adaptation changes, the main effect is a change in the timing of investment in adaptation. An increased effectiveness anticipates investment (e.g. with a 6-times increase the planner begins to invest in adaptation in 2020 rather than in 2040) whether a decreased effectiveness postpones it (a reduction of effectiveness to the 20% shifts protection investment to 2060).

Fig. 9

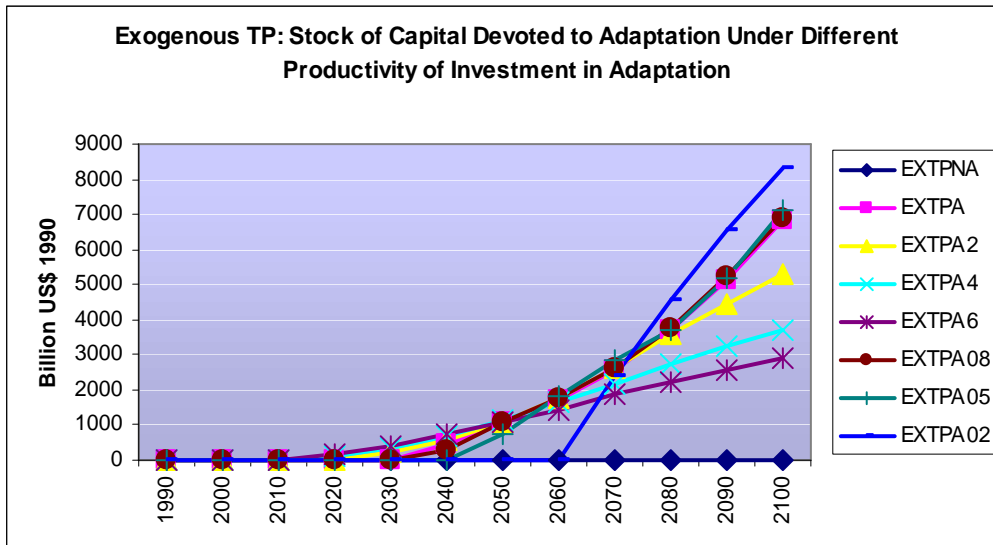
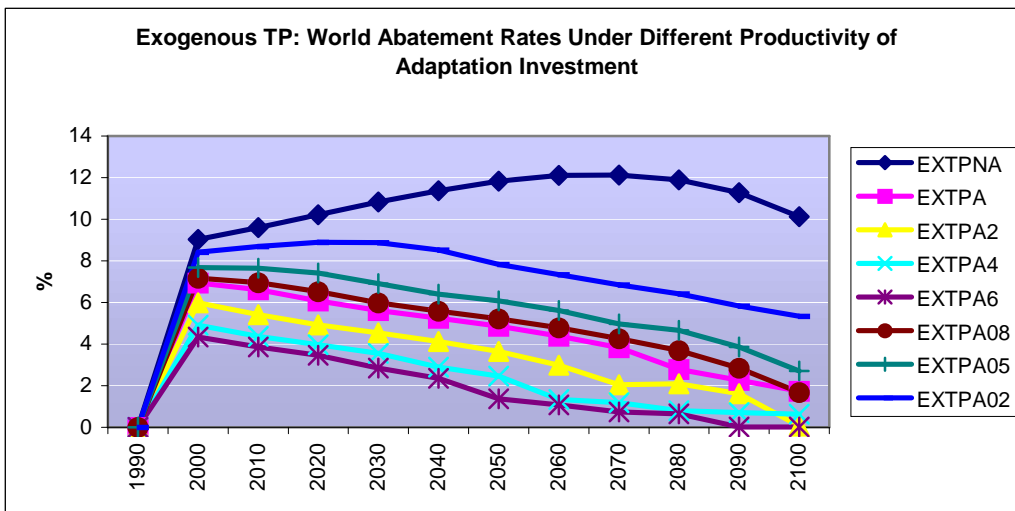
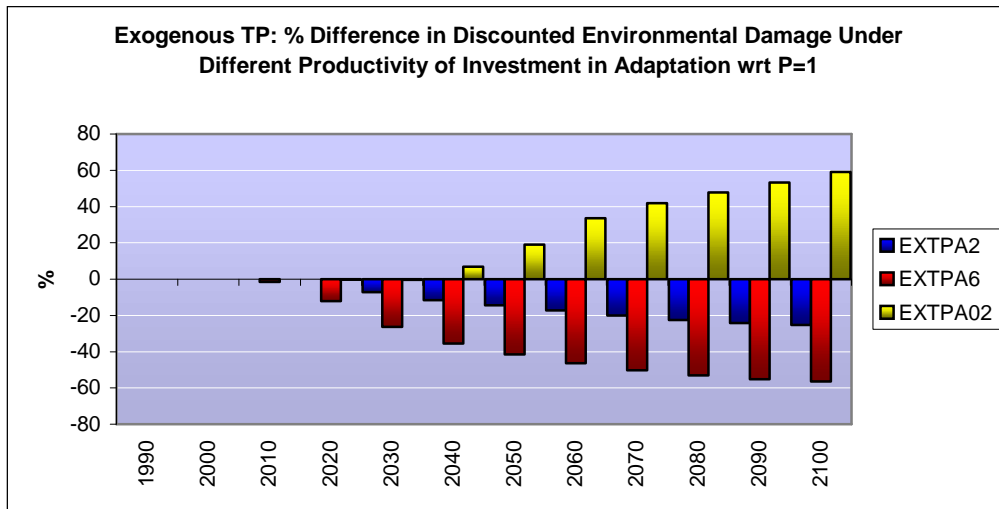


Fig. 10



Confirming expectations, mitigation moves in opposition to adaptation (fig. 9): the more effective the last, the lower the first and vice versa. For example, when adaptation is 6 times more productive, abatement is reduced roughly of the -37% in 2000 - from 6.9% to 4.2% - compared to the original level; moreover it reaches its lower bound in 2090 rather than in 2140. When effectiveness of adaptation is only 20% of the original value, abatement is increased of the 21% in 2000 and of nearly 200% in 2100. The effects on environmental damage are as expected as well (fig. 10): the decreased(increased) abatement is more than compensated by the higher(lower) effectiveness of adaptation. In 2100 discounted damage is reduced nearly the -60% respect to the original level when adaptation is 6 times more productive and increased again nearly the 60% when productivity of adaptation is decreased of the -80%.

Fig. 11



Mutatis mutandis, the effects of changes in abatement costs are in line with those of the previous experiment: a reduction in abatement costs increases abatement and decreases investment in adaptation. For example, a 90% reduction in costs fosters abatement to a + 70% in the period 2000-2070 (fig. 11) and induces a reduction of the -15% of capital stock devoted to adaptation in 2070 (fig. 12). The net effect on environmental damage is a decrease of the -4.5% in 2100 (fig. 13).

Fig. 12

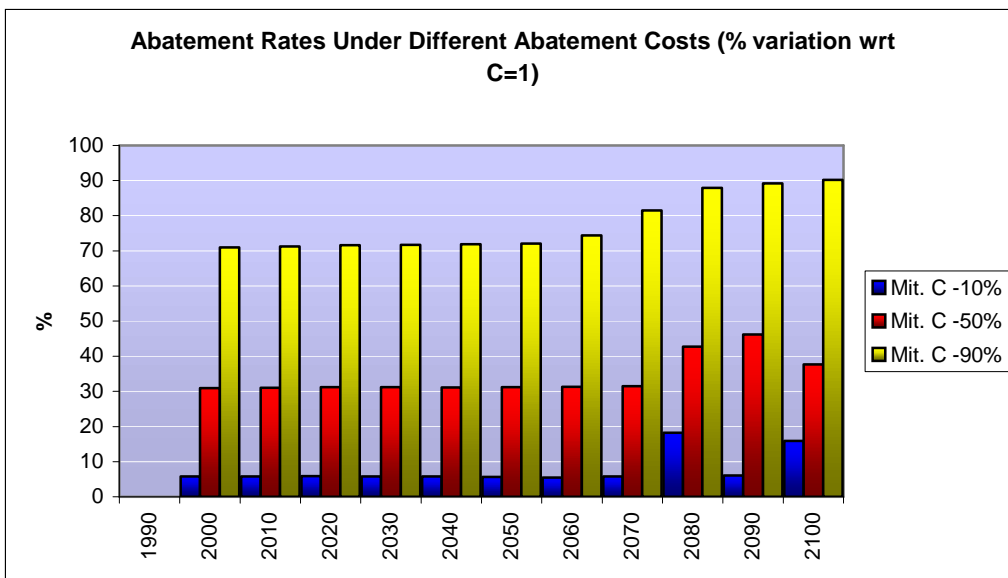


Fig. 13

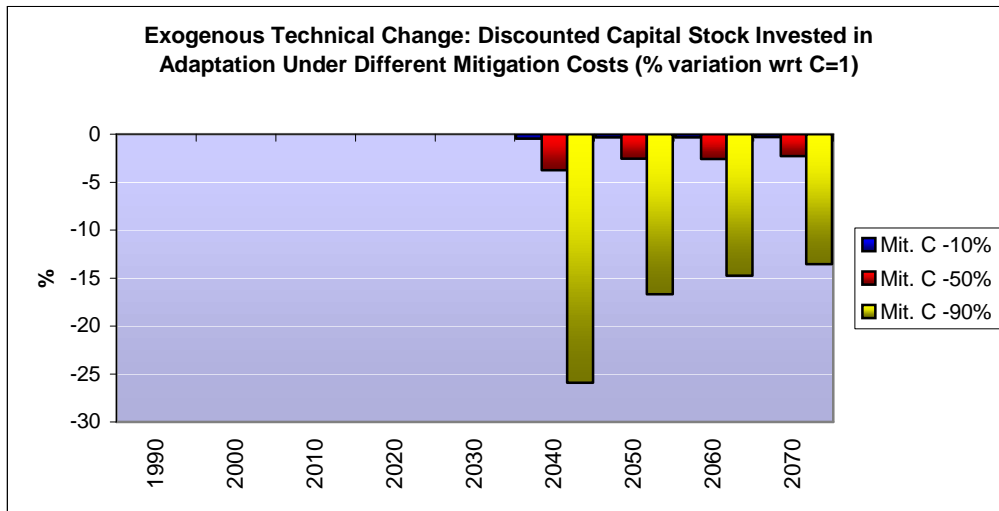
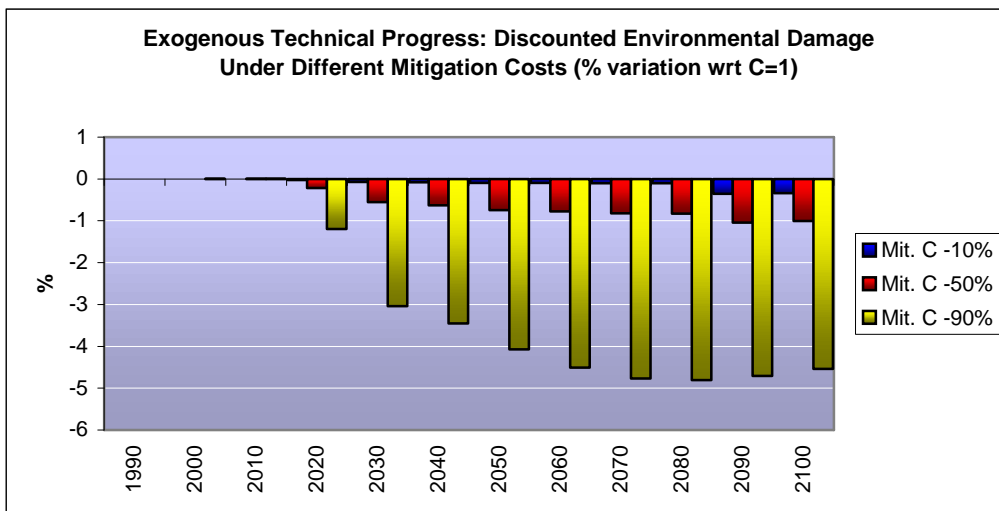


Fig. 14



The main messages of this exercise are:

- 1) Firstly the partial substitutability among mitigation and adaptation is confirmed: an increase in the effectiveness of adaptation or a decrease in the cost of mitigation boosts one policy and depresses the other.
- 2) It is also confirmed that in general mitigation is “more reactive” to adaptation than vice versa. For instance when adaptation effectiveness is doubled, mitigation is reduced nearly of the -50%, whereas halving mitigation costs adaptation is reduced the -4%.
- 3) Most importantly this sensitivity analysis points out that in a reasonable range of parameter values mitigation and adaptation remain strategic complements. For example even supposing a huge decrease in abatement costs of the -90%, still it is optimal to adapt to

partly protect against the residual or unavoidable damage. But also the opposite holds: when the adaptation technology becomes 6 times more effective, allowing by itself a damage reduction of nearly the -80% compared to the case of no adaptation, still there is room for abatement. Adaptation and mitigation basically address the same problem, damage reduction, operating in two different ways: the first acts on the effects, the second on its causes. As a consequence the positive effects of the first are experienced in the short term whereas those of the second in the long term. Moreover planned adaptation shares the features of a long-term investment strategy impacting capital accumulation patterns and thus the entire growth path of the economic system, whereas mitigation is more similar to a short-term policy with a relevant impact on current, but no (or much weaker) impact on future economic performance. These differences motivate their coexistence.

6.2. Discount rate

Environmental damages determine either the amount of resources devoted to adaptation and mitigation or their optimal intertemporal mix. Given that climate change damages are felt far in the future, the perception of time is a crucial aspect and the discount rate is likely to play a key role in shaping the results.

As can be expected, a decrease in the discount rate, reflecting an increase in the planner's preference for the future, increases mitigation, adaptation and R&D efforts (see fig. 15, 16 and 17 respectively). Moreover adaptation investment is anticipated.

Fig. 15

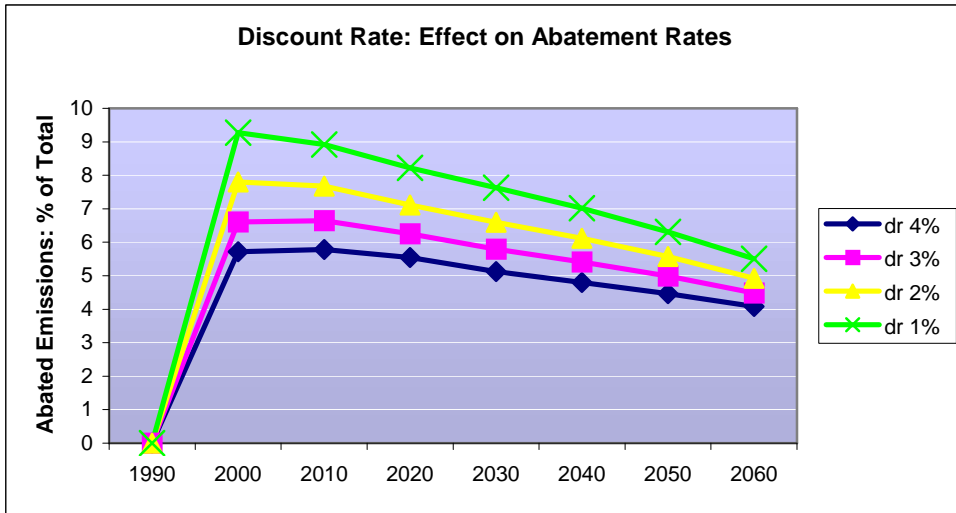


Fig. 16

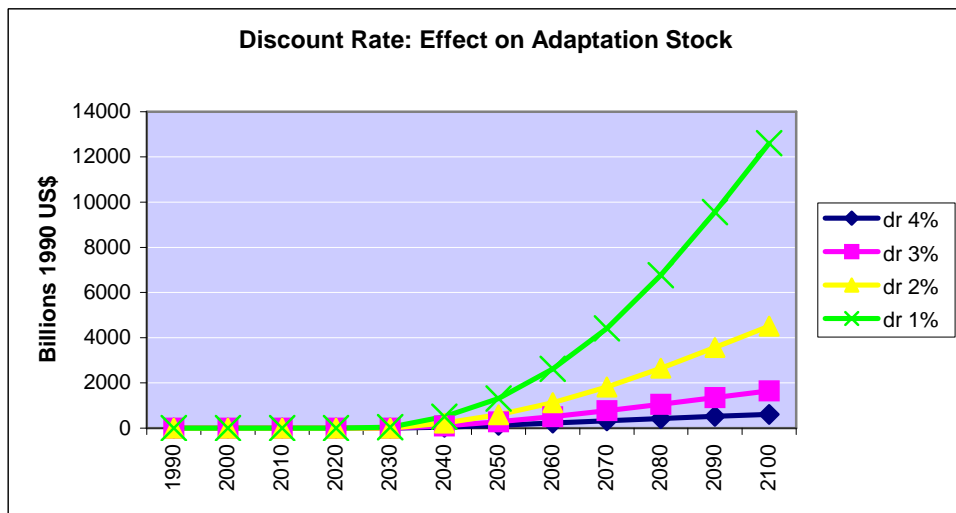
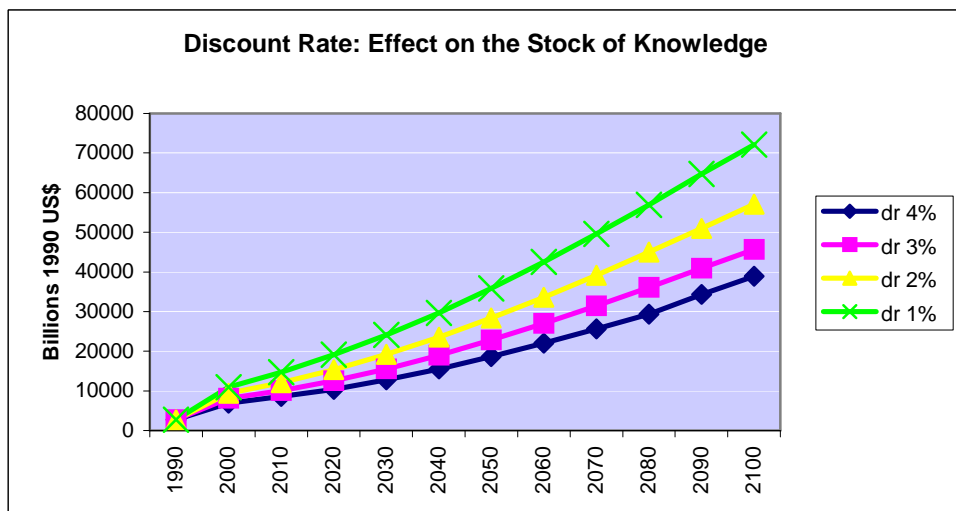


Fig. 17



Nonetheless the activity increasing *relatively* more its contribution to environmental damage reduction is mitigation (fig. 18). This reflects exactly the fact that mitigation is subjected to a longer-term inertia respect to adaptation. As the discount rate is progressively reduced, the “intertemporal advantage” of adaptation respect to mitigation vanishes and the “policy weight” is re-equilibrated in favour of mitigation.

What is also interesting to note here is that the *joint* contribution of mitigation *and* R&D to damage reduction *decreases* with the discount rate (fig. 19). Here the double influence of R&D on emissions plays its role. 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. The first effect decreases while the second increases emissions. The second prevails and offsets also the increased mitigation effort

Fig. 18

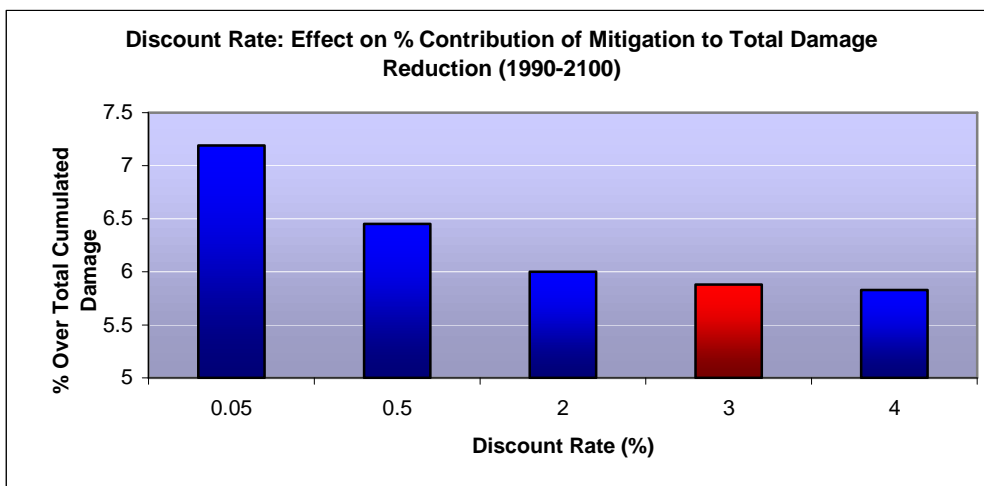
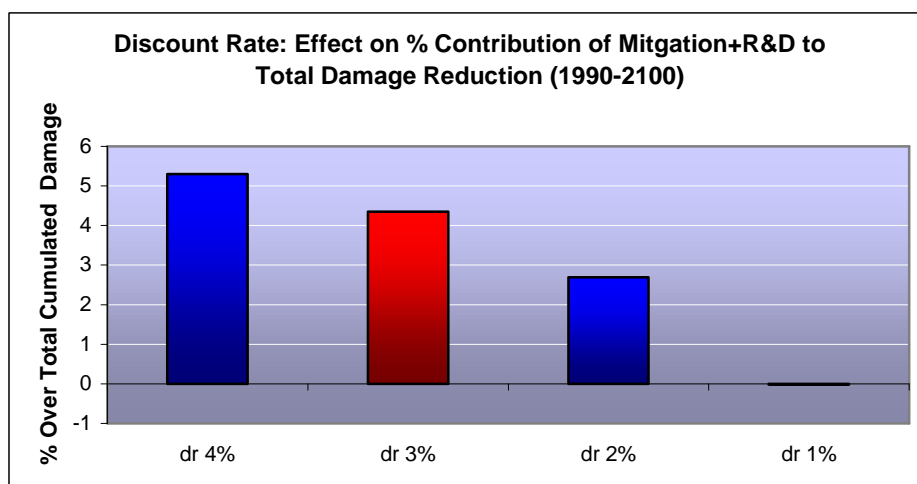


Fig. 19



6.3. Environmental Damage

Not only the weight of future environmental damage in present perception, but also its entity influence agents' behaviour. It seems reasonable to expect that agents would respond to a higher damage with a stronger effort to mitigate and adapt. At the same time if damage is increased - particularly in the first periods - this can anticipate the investment in adaptation. Here we test these hypotheses increasing environmental damage via a proper modification of the multiplicative parameter of the damage function. Essentially we are increasing the penalisation of gross output per degree of increased temperature.

Interestingly results differ substantively from the previous experiment.

First of all an increased damage induces higher mitigation and adaptation (fig. 20 and 21), but note how mitigation tends to recover the initial values as time passes. This can be understood examining interactions with adaptation. This not only increases, but is also anticipated (one and two periods respectively); this reduces the need to abate especially in the last periods.

Fig. 20

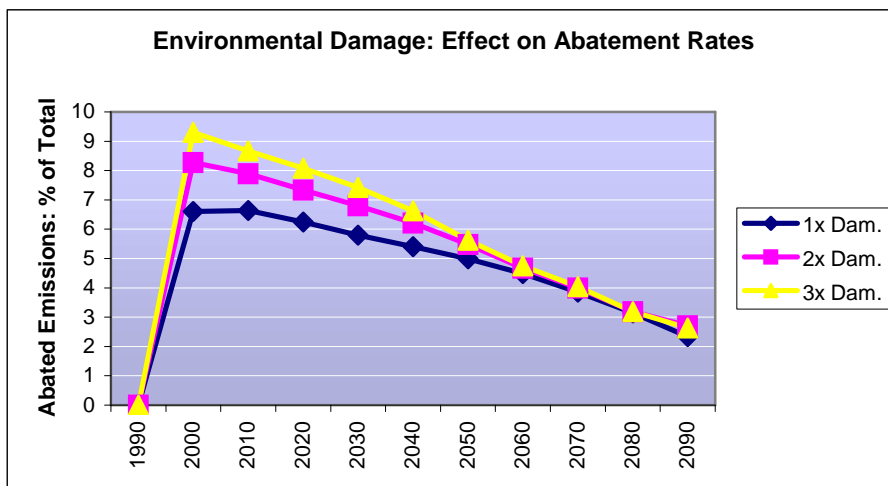
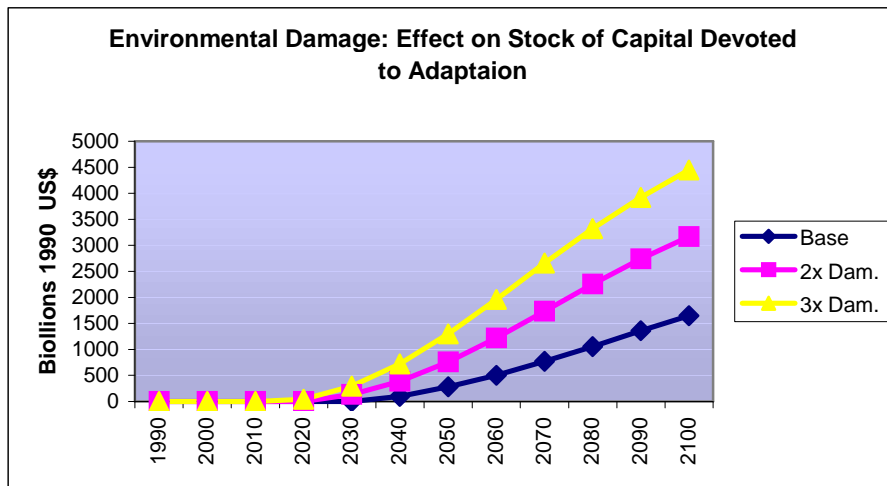
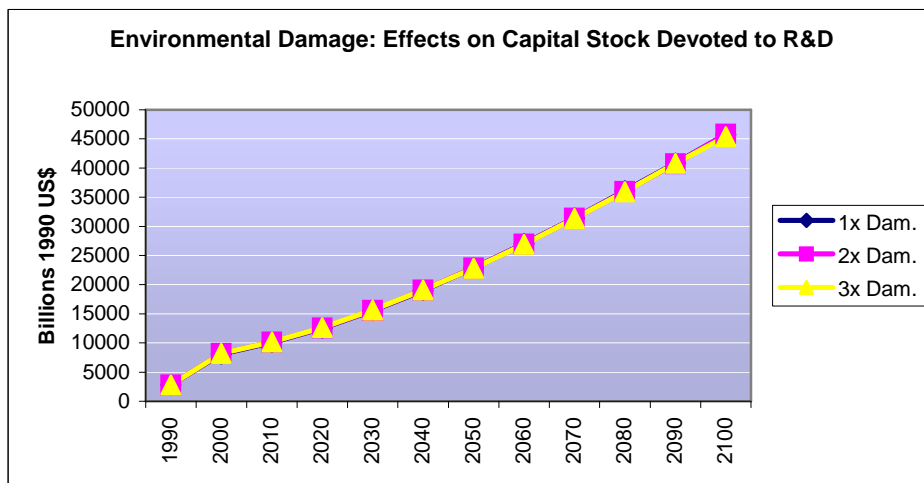


Fig. 21



Moreover, differently respect to changes in the discount rates, R&D remains basically unchanged (fig. 22). The intuition here is that the two components of R&D, one beneficial the other detrimental for the environment, more or less perfectly balance. Accordingly, doubling or tripling environmental damage tend to replicate the optimal R&D investment of the base case.

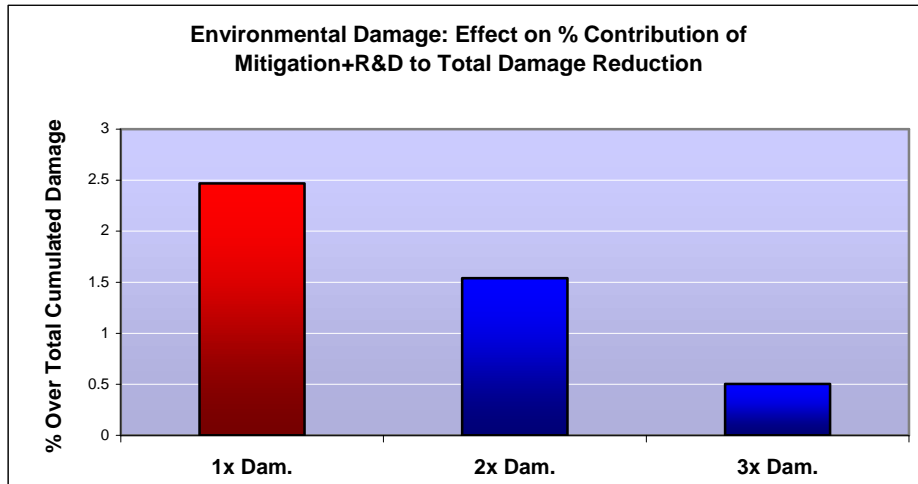
Fig. 22



Another interesting result is that increasing environmental damage, the contribution to damage reduction of mitigation respect to adaptation decreases. This can be inferred looking at fig. 23. It reports the joint contribution of mitigation and R&D to damage reduction which decrease, but we have just shown that R&D remains unchanged. This is in stark opposition to the response of mitigation to decrease in discount rates. What happens here is that, doubling or tripling damages,

all the damage is increased and not only “future” damage as with modifications in the discount rate. Accordingly there is a general shift toward adaptation that we have shown acts more quickly.

Fig. 23



7. Summary and Conclusions

This paper has proposed a possible framework to analyse the relationships existing between different strategies available to combat climate change: mitigation, adaptation and investment in technological progress.

The first important finding of this research is that all these three strategies are complementary as all of them constitute a part of the answer to the problem. This result was not obvious in particular considering the claimed high capacity of adaptation to reduce negative effects of environmental damage. We have also highlighted possible adaptation cost: at the optimum they are a tiny percent of world GDP, but they are considerably higher than those of mitigation.

Secondly we have highlighted the possible fundamental contribution of adaptation to damage reduction either under the perspective of the total damage relieved from the economic system or that of the rapidity through which adaptation benefits can be grasped. These two characteristics make adaptation an important policy option that ask to be necessarily included in any policy or scientific analysis concerning global climate change.

Thirdly we have clarified the basic difference between adaptation, investment in green R&D and mitigation. Under the benefit side the first is constrained only by a “short” economic inertia, while the other by the “long” 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 induce the optimal intertemporal resource allocation between strategies. In particular the best policy mix requires to mitigate first and adapt then.

We have in addition provided some insights about the responsiveness of one strategy respect the other. Cross elasticities are rigid, but mitigation is more responsive to adaptation than vice versa.

Finally sensitivity analyses showed that an increased intertemporal preference for the future reshuffles the policy in favour of mitigation, while the opposite happens if environmental damage is increased.

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Mathematical appendix

Model equations: endogenous technical change and adaptation

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

$$K(n,t+1) = (1 - \delta_K)K(n,t) + I(n,t) \quad (A2)$$

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

$$SAD(n,t+1) = (1 - \delta_A)SAD(n,t) + IA(n,t) \quad (A4)$$

$$K_R(n,t+1) = R \& D(n,t) + (1 - \delta_R)K_R(n,t) \quad (A5)$$

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

$$Y(n,t) = C(n,t) + I(n,t) + IA(n,t) + R \& D(n,t) \quad (A7)$$

$$Y(n,t) = \Omega(n,t)Q(n,t) \quad (A8)$$

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

$$E(n,t) = \sigma(n,t)[1 - \mu(n,t)]Q(n,t) \quad (A10)$$

$$\sigma(n,t) = [\sigma(n) + \chi(n) \exp(-\alpha(n)K_R(n,t))] \quad (A11)$$

$$F(t) = \eta \log[CC(t)/CC(0)] / \log(2) + O(t) \quad (A12)$$

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

$$T_{OC}(t+1) = T_{OC}(t) + [T(t) - T_{OC}(t)] / \tau_4 \quad (A14)$$

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:

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

$$Y(n,t) = C(n,t) + I(n,t) + IA(n,t) \quad (A7b)$$

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

$\delta_K, \delta_{CC}, \delta_A, \delta_R$ = depreciations/decays rates

b_1, b_2 = abatement cost parameters

θ_1, θ_2 = environmental damage parameters

$\beta, \eta, \tau_1, \tau_2, \tau_3, \tau_4$ = climatic parameters

σ, χ, α = technical change parameters

ϕ = utility weights