Inter-Temporal Investment in Climate Change Adaptation and Mitigation

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Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2011 AAEA&NAREA Joint Annual Meeting, Pittsburgh. Pennsylvania,

July 24-26, 2011

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Introduction

Climate change has gained increasing public attention as scientific evidence has accumulated on temperature change and its impacts. Estimates are that the world economy will suffer large future climate change induced damages, with estimated mean global GDP losses of 1.5 to 3.5% of GDP (IPCC, 2007a). It is virtually inevitable that climate change will play an even larger role in the coming decades and beyond (Rose and McCarl, 2008). Consequently, there is an urgent need for efficient climate policies and technology.

Two major policy approaches are possible

- Adaptation by adjusting to the changing climate
- Mitigation of the degree of future climate change by limiting net anthropogenic greenhouse gas (GHG) emissions or exploiting carbon sinks.

Increasing understanding of climate change physics yields the insight that mitigation will not prevent much climate change before mid-century and requires substantial effort to achieve lower atmospheric stabilization levels (IPCC, 2007c). Also in some countries, like the US, policy action to reduce emissions seems unlikely in the near term while emissions growth continues worldwide. Thus a substantial amount of climate change appears to be inevitable and adaptation will be required.

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Consequently, adaptation is receiving growing attention in policy circles with an adaptation fund being the latest international agreement (Tol, 2005; UNFCCC, 2010) and adaptation for example taking a much more important role in the emerging IPCC AR5 report.

Adaptation refers to actions that make adjustments in natural or human systems in order to moderate potential damages from climate change or exploit beneficial opportunities. Burton (2004) argues adaptation is extremely common and as old as mankind but that it is largely to a stationary spatially or temporally varying climate without considering future climate change. Carter et al. (1994) classifies adaptation as autonomous and planned as do all of the subsequent IPCC reports and the most recent ones like UNFCCC (2010), Parry et al. (2009) and World Bank (2010). Autonomous adaptation involves the reactions that natural and human systems will undergo in response of changing conditions, irrespective of any policy plan or decision. Planned adaptation, on the other hand, is the deliberate policy options or response strategies, aimed at altering the adaptive capacity or facilitating specific adaptations. For example, R&D investment in new technical or management options. This paper is largely concerned with planned adaptation.

Increasingly there appears to be recognition of the need to simultaneously implement adaptation and mitigation. However, this presents significant policy challenges. Firstly, both the policy and research communities traditionally have treated such two responses independently. Secondly, they are, substantially, rival goods since investment in one diverts the resources available to the other. More fundamentally, there is a lack of both conceptual and empirical information that explicitly considers adaptation and mitigation together. Only recently have policymakers expressed an interest in exploring the interrelationships between them (IPCC, 2007c). In this paper we follow the lead of de Bruin et al (2009) and do a further exploration of the optimal inter-temporal balance between mitigation and adaptation.

Literature review on modeling adaptation and mitigation

Integrated assessment models (IAMs) have become a common tool for assessing climate change related strategies by typically combining economic activities and geophysical scenarios to estimate the costs and benefits of various options over time (IPCC, 2007c). However, so far the climate policy strategies addressed in the majority of IAMs are predominantly limited to mitigation. Progress on adaptation is rarely measured due to an absence of measurable outcomes or indicators, leading towards to the reluctance of governments to invest in adaptation interventions (Berrang-Ford et al, 2011; Burton, et al, 2002). In most cases, adaptation, when considered, is either a choice variable among technological options or assumed to be optimal and already included in the damage function (Nordhaus, 1994; Schneider, 1997; Patt et al., 2010). Furthermore, while some models include adaptation cost into damage estimates, it is typically not explicitly distinguished nor is the level of adaptation optimized (Fankhauser, 1994; Yohe et al., 1996). Several authors however have tried to deal with both issues in modeling

- Hope et al., (1993) took a first step with the PAGE (Policy Analysis of the Greenhouse Effect) model treating adaptation as an explicit control variable by allowing a binary choice between no adaptation and aggressive adaptation. However, restricting adaptation measures to two extreme choices is contradictory with existing empirical literature on the costs and effects of adaptation (de Bruin et al, 2009).
- Tol (2007) considered adaptation to sea level rise with FUND (The Climate Framework of Uncertainty, Negotiation and Distribution) model concluding that adaptation is very important and needs to be traded off with mitigation. However, Tol’s study follows Frankhauser (1994), and assumes protection cost is exogenous plus is limited to coastal protection.
- de Bruin et al., (2009) extended the DICE model to consider both adaptation and mitigation. They find that adaptation is a powerful option for reducing the potential costs of climate change in earlier periods, while mitigation does so in later periods (de Bruin et al., 2009). In doing this they assume that adaptation investment costs and benefits of adaptation are “instantaneous” and not persistent. Their assumptions on avoided damages due to adaptation are largely based on a survey by Tol and Fankhauser (1998) that focused on coastal protection.
- Bosello (2008) examined the optimal path of planned adaptation, the optimal inter and intra temporal mix between adaptation, mitigation and R&D in an extension of the FEEM-RICE growth model. His qualitative results showed that adaptation and

mitigation are strategic complements for solving climate change problem. He calibrated adaptation costs in a simple exponential form basing on the old survey by Tol and Fankhauser (1998) because of the scarce information on adaptation and residual climatic damages (Bosello, 2008).

- Bosello et al, (2010) did a study with the AD-WITCH model and assessed the optimal timing of mitigation and three different modes of adaptation (anticipatory adaptation, reactive adaptation and R&D in adaptation). Results indicated that the joint implementation of mitigation and adaptation is welfare improving, in which mitigation starting immediately while adaptation was delayed until somewhere later when gross damages were higher. Even though a more sophisticated description of adaptation strategies are implemented, correspondence is far from perfect due to the uncertain relationship between adaptation costs and protection levels.
- Patt et al. (2010) summarized how existing integrated assessment models describe adaptation and suggested many ways that could be applied to improve the treatment of adaptation within an integrated framework. They concluded that better modeling of adaptation costs and benefits could have important implications for defining mitigation targets. However, they did not do any quantitative study.

In this work we again study the balance between adaptation and mitigation extending the research of Bosello et al (2008, 2010), de Bruin et al (2009) and Patt et al (2010). In particular we also modify DICE but employ different assumptions than de Bruin et al. More specifically we employ

- A less restrictive assumption on the persistence of effects from adaptation investment so that the proactive adaptation can be taken to avoid some damages.
- A more broadly based damage function that is based on economy wide possibilities drawing on the study of Parry et al (2009).

The conceptual model

Before conducting a numerical study, we provide a conceptual framework for the joint optimization of adaptation and mitigation. A mitigation only optimal control model is,

$$\min_{m} TCD = \left\{ \; q(c) + IM(m) \; \right\} \quad \textbf{(1)}$$

$$\text{s.t. } c = \text{g}(m)$$

where q gives the losses as a function of realized climate change (c), m the mitigation effort, *g(m)* gives the amount of climate change realized given mitigation effort *m*, and *IM(m)* the cost of mitigation. In this setup q is an increasing function of the amount of realized climate change (c), *IM* is an increasing cost function of m, g(m) is a function that exhibits decreases in realized climate change as mitigation effort increases. Total climate damage (TCD) is the summation of mitigation cost and total climate change impact or damage cost (TIC) (As portrayed in Fig 1 (a)). The optimal mitigation level m_1^* and mitigation cost IM_1^* corresponding to the lowest point on TCD curve illustrates the optimal solution.

Now we add adaptation in:

$$\min_{m,a} TCDA = \{ q(c,a) + IM(m) + IA(a) \} \quad \textbf{(2)}$$

$$\text{s.t. c=g(m)}$$

where c, *m*, *g(m)* and *IM* have the same definitions as above and the new parameters are

- *a* the level of adaptation effort,
- IA(a) the cost of investment in adaptation

We also change the loss function q so it is the function of realized climate change and the degree of adaptation effort.

The resultant optimal investment simultaneous levels of adaptation a_2^* and mitigation m_2^* from model (2) differ from the above mitigation-only investment m_1^* level. We illustrate the solving procedure in Figure 1(b) and (c). At a certain level of mitigation, total climate impact cost after adaptation (TIC) is the sum of residual damage cost (RDC=q(c,a)) and adaptation cost (see Fig 1(b)); while total climate damage after adaptation (TCDA) is the sum of total impact cost (TIC) and the associated mitigation cost (see Fig 1(c)). Since the optimal adaptation level minimizes the total impact cost, the lower curve TIC_1 in Fig 1 (c) is the least impact cost with optimal adaptation efforts over every mitigation level; while the upper curve TIC_2 is the highest impact cost with least optimal adaptation (no adaptation or aggressive adaptation). The range bounded by TIC_1 and TIC_2 corresponds to the range of total impact cost when adaptation level is varied. The mitigation cost IM_2^* corresponding to the minimal $TCDA_1$ and is the optimal mitigation investment. The assumed residual damage curve (RDC) in Fig 1(b) is corresponding to the optimal mitigation level m_2^*. Thus, a_2^* and IA_2^* which minimizes the total impact costs (TIC) are the optimal level of adaptation effort and cost respectively. As indicated in Fig 1(c), total climate damage D_2^* with optimal mitigation and adaptation efforts is less than D_1^* which is the damage with mitigation only. However, the exact amount of IA_2^* quite depends on the shape of adaptation cost and residual damage curve.

Adding explicit adaptation to DICE

Now we discuss an empirical counterpart to the above theoretical model that we developed to examine optimized adaptation and mitigation. To do this, we follow de Bruin et al. (2009) and create a similar extension of the DICE model (Nordhaus and Boyer, 2000).

In DICE, global regions are assumed to maximize social welfare function subject to a number of economic and geophysical constraints. DICE represents mitigation activities allowing “climate investment” that reduces current consumption and non-climate investment while reducing future climate change and associated damages. The DICE model assumes optimal reactive adaptation wherever possible but largely ignores proactive adaptation activities and costs.

To overcome the above limitations, de Bruin et al. modified the DICE model by implementing proactive adaptation as an explicit decision variable. In their AD-DICE model, proactive adaptation is a control variable that only has an effect in the current period so that one period’s adaptation does not affect damages in the next period. Such an assumption is restrictive since some types of adaptive strategies have a “stock” nature that would have long lived effects. For example, building a seawall or identifying genes for drought resistant crop varieties have effects for a longer period than just the current one. Moreover, adaptation restrictions applied in their model calibration are generally based on the earlier literature and reflect a limited set of technological adaptation options for limited adaptation possibilities so we include some more recent and broader based data.

Improving adaptation features

In our model, we follow some approaches used in AD-DICE model (de Bruin et al., 2009), but differ in three major ways:

1) We introduce features that create a stock of adaptation effort based on proactive investment.

2) We introduce an alternative form of the adaptation production function i.e. the relationship between climate change damages abated and adaptation investment. In particular we calibrate the function to data from Parry et al (2009)'s work on the relationship between adaptation costs and residual damages.

3) We explicitly model adaptation investment as a use of capital diverted from total net output over time.

To add the "stock" nature of proactive adaptation to DICE/AD-DICE, we add adaptation a capital stock account, which accumulates as an adaptation investment over time and also depreciates over time. Therefore, the resulting optimal adaptation decisions adjust to current and future climate change damages rather than those in a single decade. Mathematically we denote the choice of adaptation investment level in period t as $IA(t)$. The state variable $SA(t)$ is added to represent the stock of adaptation for decade t as:

$$SA(t+1) = (1-\beta)^{10} SA(t) + 10IA(t) \qquad \textbf{(3)}$$

with the initial condition $SA(t) = 0$, where β is the depreciation rate of capital invested in adaptation. We initially assume β is 0.1 per year so that the adaptation investment depreciates by $(1\text{-}0.1)^{10}$=0.35 each period. Sensitivity analysis in later sections investigates the implications of different depreciation rates.

In AD-DICE, de Bruin et al modify the net damage function to be a combination of separable adaptation costs and residual damages. In our model, we do not try to separate such autonomous (reactive) adaptation costs from damages, since they are implicitly part of climate change losses in the real world. We assume that planned adaptation investment is done by public interests to avoid the negative effects of current and future climate change, thus restate the realized damages D_t as:

$$D_t = RD_t(GD_t, A_t) \quad \textbf{(4)}$$

where RD_t is a function giving the "left-over" climate change induced damages (or residual damages) after the effects of adaptation efforts are considered, GD_t is the gross damages which is adjusted for mitigation effort and for autonomous adaptation, A_t the planned adaptation effort.

Regarding the form of the residual damages function, AD-DICE and many other available IAMs (e.g. FEEM-RICE, AD-WITCH) do not use a functional form that allows the possibility of unadaptable damages (for discussion of the concept see Parry et al (2009) , rather using forms that assume residual damages can be totally reduced to 0 under full adaptation. We use an alternative form as portrayed in Figure 2, where damages decrease non-linearly with adaptation investment and a degree of unavoidable damages is indicated by the horizontal dotted line that the curve asymptotically approaches. Accordingly, the functional form of residual damages is:

$$RD_t(GD_t, A_t) = GD_t * (1 - A_t), \quad 0 \le A_t \le 1 \ (5)$$

$$1 - A_t = \alpha + (1-\alpha)e^{-rSA_t} \quad (6)$$

where α is the percentage of unavoidable damages; A_t is the normalized resultsing level of adaptation in year t and ranges from 0 (no protection) to 1 (full protection). Equation (6) thus gives the proportion of residual damages as a function of adaptation investment stocks (SA) and unavoidable damages (α).

To empirically specify these functions, we calibrate the function reflective of a statement in Parry et al. (2009) which indicates "unavoidable impacts are about one fifth of all damages in 2030 and, over the longer term, may account for up to two-thirds". For simplicity, we take the unavoidable damages as 0.2 for our parameter α in equation (6). Moreover, Parry et al. (2009) stated that avoiding the first 10% of damage will be disproportionately cheaper than the other 90%. If we define MARR as the marginal adaption reduction rate, then in Figure 2, point B, where 1/MARR=1, can be taken as a "breakpoint" with corresponding damage level *d* and adaptation cost level *sa*; the slope 1/MARR>1 for the points (on the curve) above (*sa,d*) and 1/MARR<1 for those below (*sa,d*). Thus *d=0.9GD*, and 10% of damages above *d* can be reduced with lower adaptation costs, while the difficulty increases with the further damages to be reduced. At point (*sa,d*), the incremental adaptation cost equals the reduced damages,

$$\left.\frac{\partial(RD_t / GD_t)}{\partial SA_t}\right|_{SA_t=sa} = -(1-0.2)re^{-r(sa)} = -\frac{1}{MARR} = -1$$

and

$$GD_t * [0.2 + (1-0.2)e^{-r(sa)}] = 0.9GD_t$$

hold simultaneously. The resultant value of *r* is $10/7$. Thus, the parameters in equation (6) are specified as α=0.2, *r=10/*7.

Because climate change risks have still not been factored into many development decisions, we feel not much planned adaptation has taken place. We thus assume for simplicity that proactive adaptation costs are not part of DICE estimated damages. Moreover, our model does not address autonomous adaptation explicitly. Instead, the damages are meant to represent the climate change impacts net of reactive adaptation. Accordingly, the gross damage equation in our model takes the same form as in DICE in which damage-output ratio is assumed to be a quadratic function of global temperature increase (Nordhaus, 2009):

$$GD_t / Y_t = \pi_1 TE_t + \pi_2 TE_t^2 \qquad (7)$$

where Y_t is net output in year t, TE_t represents the average temperature change since 1900.

To complete our model, we make the same assumption as in Bosello et al. (2010) that decisions on the levels of adaptation and mitigation are separable but compete for investment funds. Therefore, we add a term to the identity relating total output with consumption and investment that includes adaptation investment:

$$Q(t) = C(t) + I(t) + IM(t) + IA(t) \quad (8)$$

where $Q(t)$ is the net output of goods and services, adjusted downward for climate change damages after abatement; $C(t)$ is consumption; $I(t)$ is “traditional” investment contributing to the production capital stock only; $IM(t)$ represents the mitigation investment and $IA(t)$ represents the adaptation investment.

Model use

Now suppose we use the modified DICE model hereafter AD-DICE++ to examine the optimized roles of adaptation versus mitigation. Note a verification run shows that if we set adaptation investment to zero that the model reproduces the original results of DICE model. However when adaptation is allowed to be nonzero, the optimal decisions change. So let us use the model to investigate

- What are the social optimal allocations of mitigation and adaptation investment over time?
- Is it beneficial to invest in a mixed strategy of both adaptation and mitigation?
- What are the relative contributions of adaptation and mitigation to damage reduction?

In our analysis, we build AD-DICE++ on top of the GAMS version of the DICE-2007 model as downloaded from http://nordhaus.econ.yale.edu/DICE2007.htm.

Optimal investment in adaptation and mitigation

Figure 3 portrays the investment results with and without proactive adaptation. There we see that when optimal adaptation investment is undertaken, the optimal mitigation investment level is far less than that in the without adaptation case before year 2230. Total mitigation investment averages 55% lower than under the mitigation only case. The optimal flow of adaptation investment increases over time and planned adaptation uses more than 50% of the total climate related investment expenditures in the first 220 years but decreases to 30% and even lower afterwards with mitigation efforts dominating from thereon (see Figure 4). Reasons for such different investment time paths are discussed in the later section. These results are similar to what de bruin et al. estimated that adaptation is the main climate change damages reducer in the earlier periods after which mitigation dominates. But in our model there is about 50% more adaptation investment with longer prevailing periods than in AD-DICE model due to the stock nature. Different from the conclusion made by Bosello et al (2008, 2010) that aggressive mitigation is the starting point and it is not worthy to invest in adaptation when damage stock is low, our results demonstrate that taking adaptation in earlier stages simultaneously with reduced mitigation investment is more cost-efficient than postponing it till the damage stock is sufficiently large.

The effectiveness of adaptation

Figure 5 shows total climate change damages with and without the planned adaptation investments allowed. It is clear that total damages are reduced over all periods through use of planned adaptation. Also with planned adaptation active, total gross world product (net of abatement and damages) averagely increases by 15% (Figure 6), indicating that an integrated adaptation and mitigation strategy is more effective. Notwithstanding the effects of lower mitigation in the form of higher CO_2 equivalent emissions in the earlier periods, the benefit of planned adaptation in terms of avoided damages increases up to 4.3% of total net output before year 2230, after which mitigation plays the major role in reducing damages (Figure 7). The results indicate that under the assumptions in our model adaptation is the dominant strategy for reducing vulnerability to climate change during the following two centuries, and is initially more beneficial than only applying mitigation. Moreover, Figure 8 implies that adaptation investment diminishes with the increase of (percentage) unavoidable damage whereas the mitigation costs goes up (Figure 9).

Temporal management of adaptation and mitigation

The above results indicate that adaptation is an effective damage reduction strategy and a complement to mitigation. However, because of the finite resources, they are also competitive in that investment capital use for one diverts it from the other and both divert funds from other output enhancing investment. Thus, studies about the relative shares are of interest.

Figure 10 highlights that adaptation is the dominant climate change damage reduction means for about two centuries after which mitigation dominates. This optimal time path of relative shares between the two strategies is mainly due to:

1) <u>The mechanism of adaptation and mitigation is different.</u>

   Mitigation is any action taken in advance to eliminate or reduce the long-term risk and hazards of climate changes through changes in the climate. Adaptation, on the contrary, refers to the direct adjustment capacity for climate change to moderate vulnerability. The mitigation investment controls GHG emissions and the atmospheric stock of GHGs at the cost of reduced consumption. Mitigation has to be undertaken well to counteract the damages whereas adaptation can be much more immediate. However, even the most stringent mitigation efforts cannot avoid short term impacts of climate change, which makes adaptation essential in addressing short-term impacts and generally stable after the climate change is close to being stabilized due to the long run mitigation efforts.

2) <u>The timing of results from adaptation and mitigation investment is different</u>

   Initially, damage stocks are low hence marginal benefit of reducing carbon emissions is also low. The results of mitigation investment are constrained by climatic inertia and the slow workings of the carbon/GHG cycle and hence take more time to be effective. While potentially more expensive, adaptation could have larger effects on impacts more quickly. Accordingly, it is not profitable to invest a lot in abatement in the short-run and rather adaptation is pursued which has a relatively lower cost and direct effect in adjusting to the first 10% damages. The results of mitigation investment are constrained by climatic inertia and the slow workings of the carbon/GHG cycle and hence take more time to be effective. Well planned adaptation avoids the inefficient costs of mitigation at the beginning, while the effectiveness of mitigation in reducing GHG emissions prevails later when damage stock is big enough that adaptation is not cost-efficient.

Sensitivity analysis

The results in de Bruin et al arise under an assumption that adaptation in one period does not have long lasting effects into future periods i.e. with a very high depreciation factor (β). We feel some adaptation actions can have longer term effects and thus added stock consideration and a depreciation factor into the model. To see the effect of such an assumption we ran the model with the base (0.1) and two alternative depreciation rates (per year) 0.05, and 0.5. As one could expect, with the increasing of depreciation rate, the amount of adaptation investment decreases (Figure 11). This result is consistent with the intuition that a higher depreciation rate depreciates more returns of adaptation investment in future, and thus would lower the capital invested in adaptation. Moreover, if we assume that adaptation investment depreciates fast which endures a very weak stock characteristic, the results of observed adaptation and mitigation costs move closer to those in de Bruin et al.'s model where adaptation is proposed as a flow variable only.

Concluding comments

Currently, different dimensions of mitigation strategies have been investigated in policy analysis, and the primary focus of international climate policy has been on the use of mitigation through cap-and-trade and energy substitutes with little heed paid to adaptation (IPCC, 2007b).

Adaptation is usually modeled as optimally applied and not an investment option (as argued in de Bruin, 2009). However, planned adaptation will require levels of public investment (see estimates in the UNFCC and World Bank reports) as is behind the adaptation fund that is now emerging. In terms of an overall investment shared between mitigation and adaptation our simulation shows that while mitigation tackles the long run cause of climate change, adaptation tackles the short run reduction of damages and is more preferred when damage stocks are small as also found in de Bruin et al but contrary to Bosello et al (2008, 2010)[i]. Instead of taking adaptation as a 'residual' strategy adjusting to the non-accommodated damages by mitigation (Bosello et al., 2010), we find well planned adaptation is an economically effective complement to mitigation since the beginning due to the interdependent nature between mitigation and adaptation. The near term nature of the benefits given an adaptation investment makes it an important current policy option.

In many parts of the world, current levels of projected investment in adaptation are considered far from adequate, and lead to high vulnerability to the current and future climate, including the effects of systematic changes, variability and extremes, which Burton (2004) called the 'adaptation deficit'. Most current Integrated Assessemnt Models do not explicitly model adaptation or are limited to autonomous adaptation. Some have modeled adaptation but under strong assumptions like no adaptation effect on future damages or no unavoidable climatic damages. Here we extended that work to have persistent adaptation plus unadaptable damages and investment competition.

Our temporal investment allocation results show that both adaptation and mitigation are simultaneously employed strategic complements much as found in de Bruin et al. We do show in our results a great immediate role for adaptation with a longer run transition to mitigation as the damages from GHG concentrations increase.

It is worth noting that we have a number of assumptions herein could be relaxed in future research including

- A lack of modeling of any direct interaction between adaptation and mitigation in terms of their specific effectiveness and trade-offs.
- A lack of consideration of regional differences.
- Omission of extreme events and other risks.

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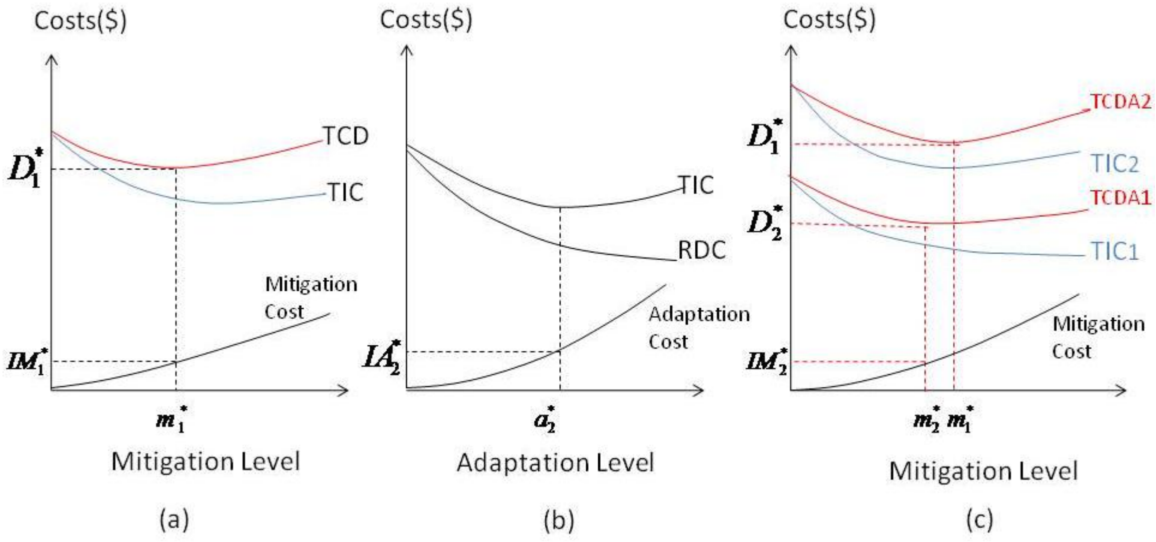

Figure 1. Optimal adaptation and mitigation investment. Panel (a) shows optimal investment in mitigation in the absence of adaptation; Panel (b) the corresponding optimal adaptation investment at the optimal level of mitigation; Panel (c) optimal mitigation investment when alternative adaptation efforts are introduced

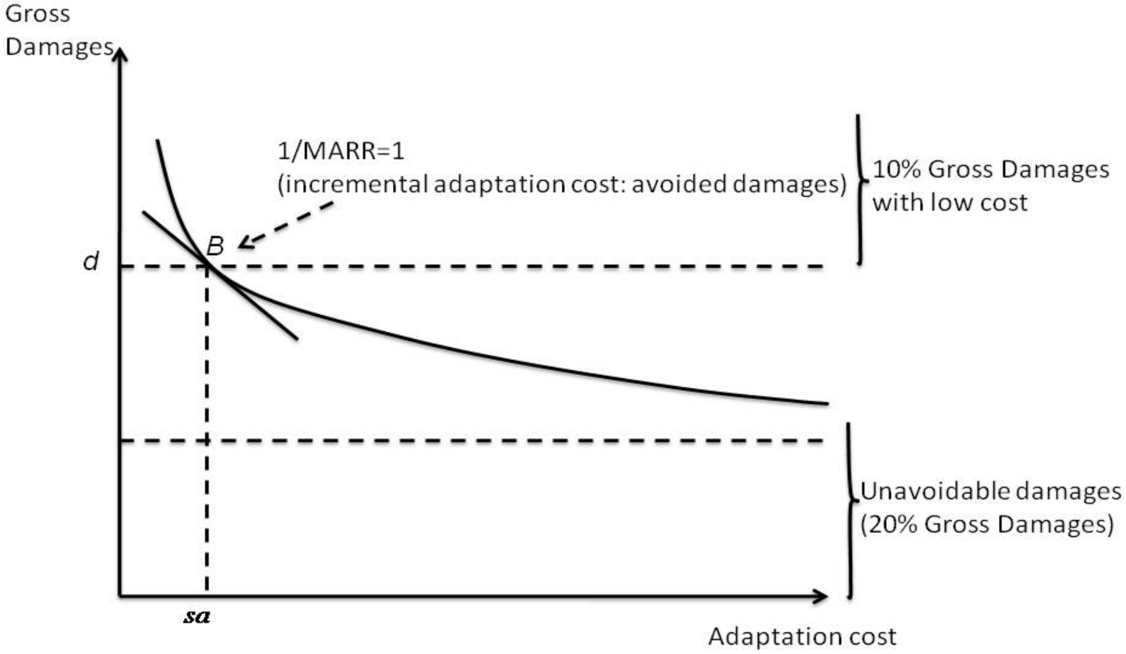

Figure 2. Portrayal of relationship between adaptation investment, residual damages, and unavoidable damages

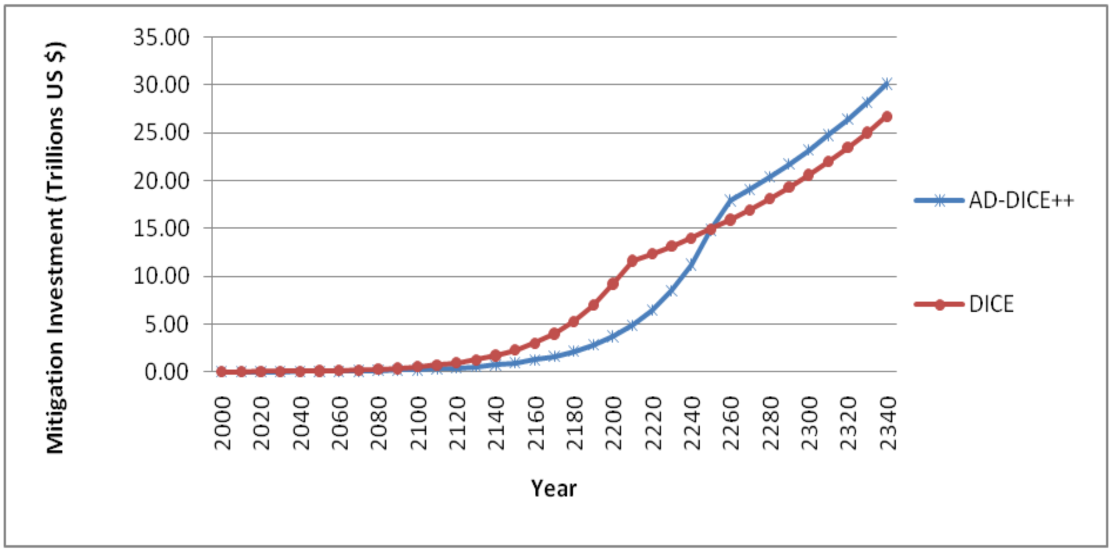

Figure 3. Results of optimal mitigation investment with and without planned adaptation investment allowed

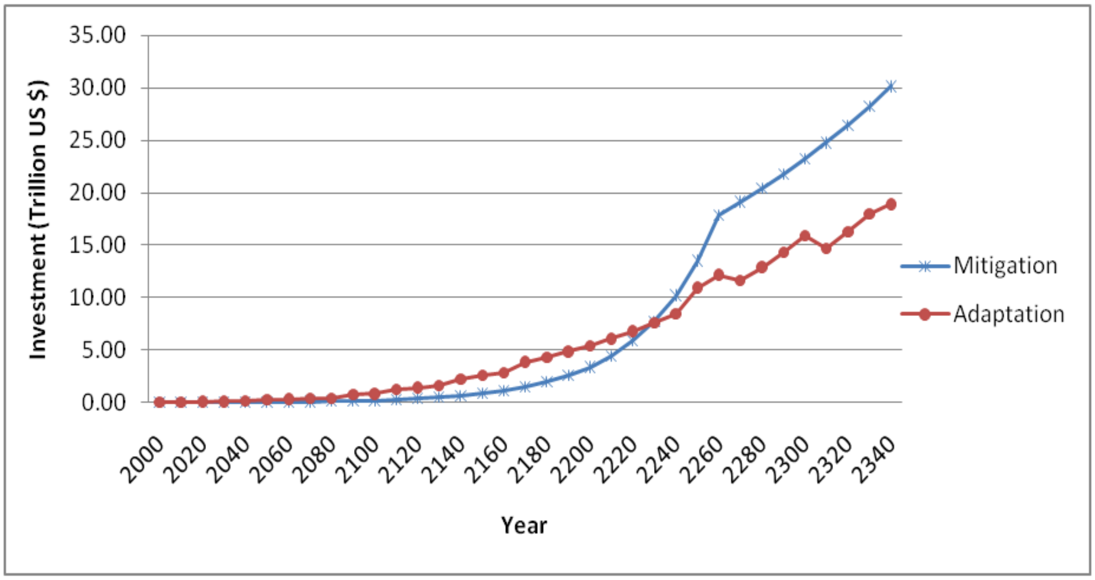

Figure 4. Optimal adaptation and mitigation investment in the model with both planned adaptation and mitigation investment allowed

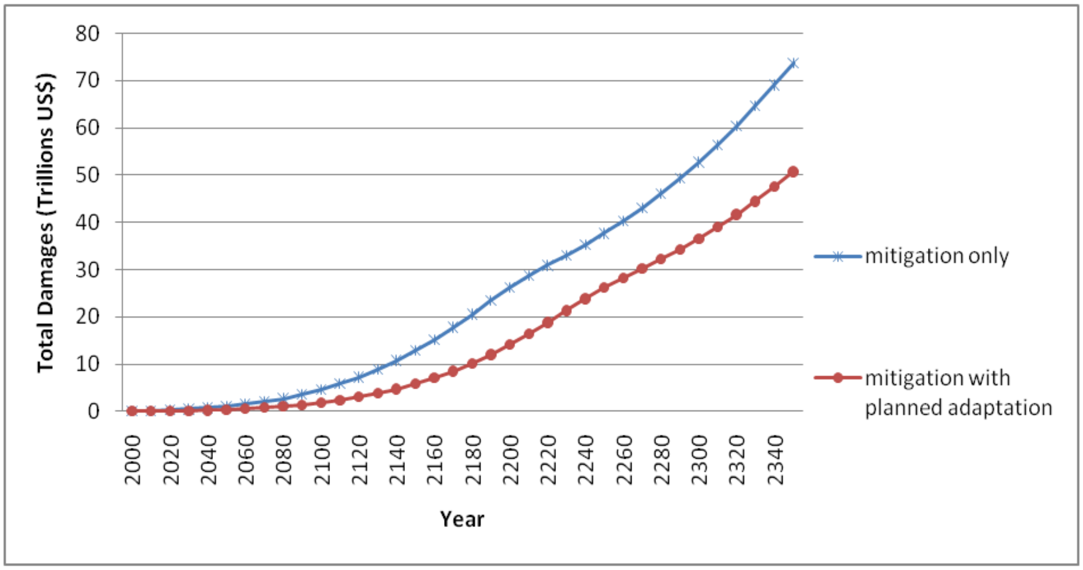

Figure 5. Total damages with and without planned adaptation

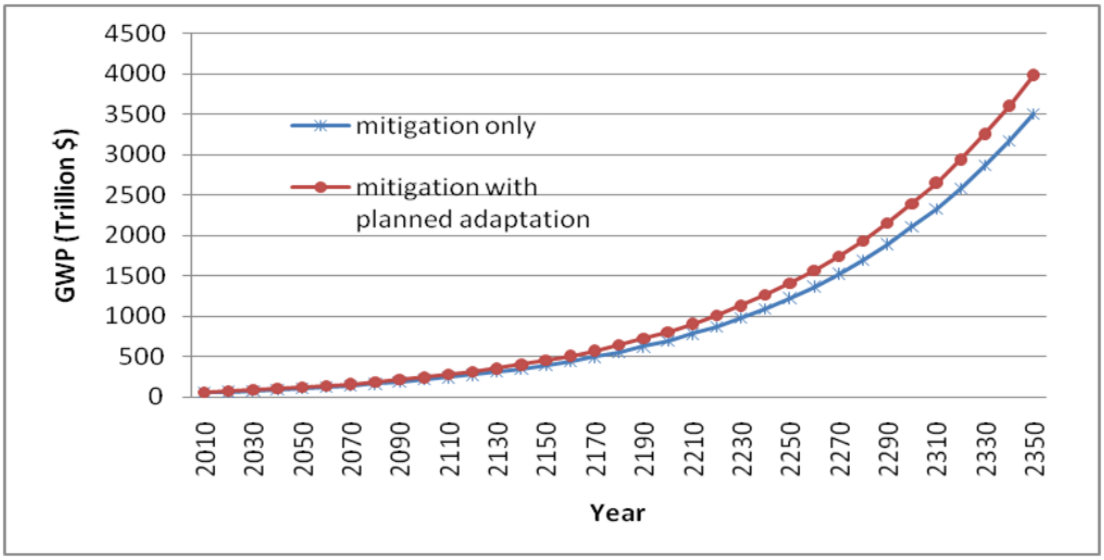

Figure 6 Gross world productivity with and without planned adaptation

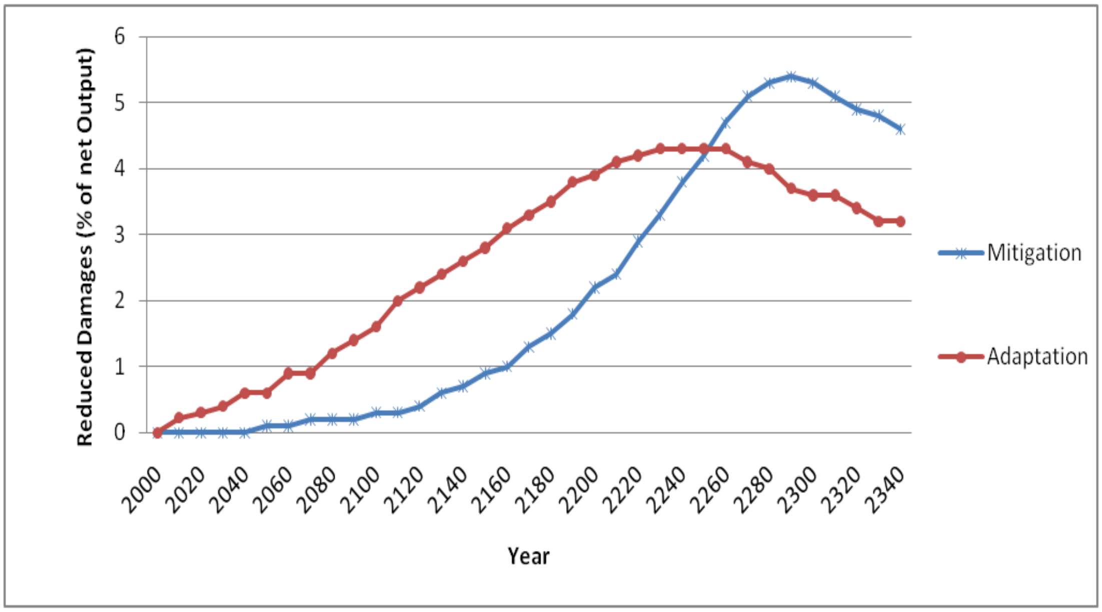

Figure 7. Benefit of planned adaptation and mitigation within the model both strategies are allowed

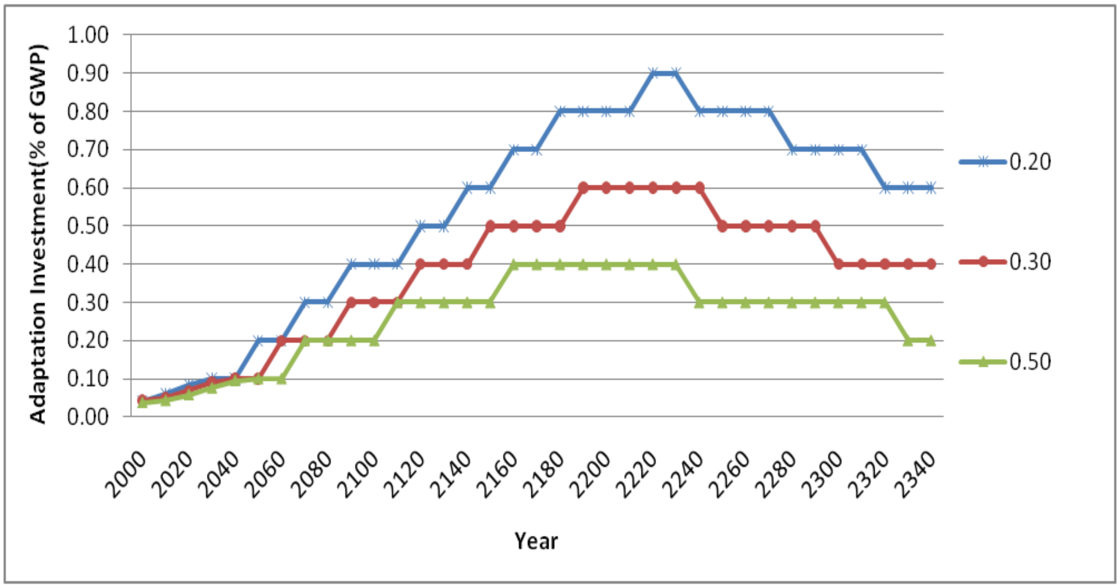

Figure 8. Planned adaptation investment with alternative level of unavoidable damages

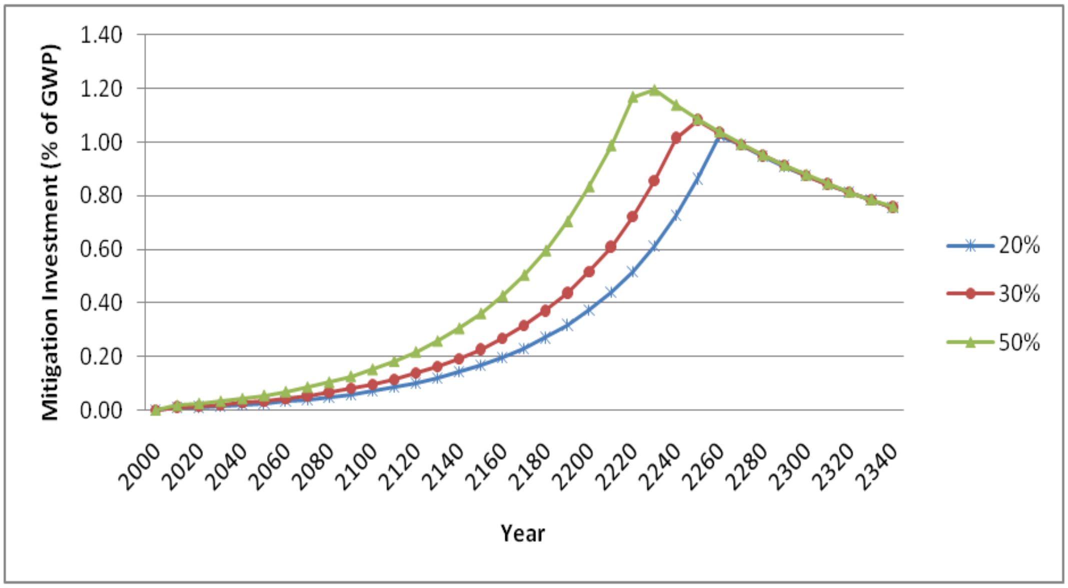

Figure 9. Mitigation investment with alternative level of unavoidable damages

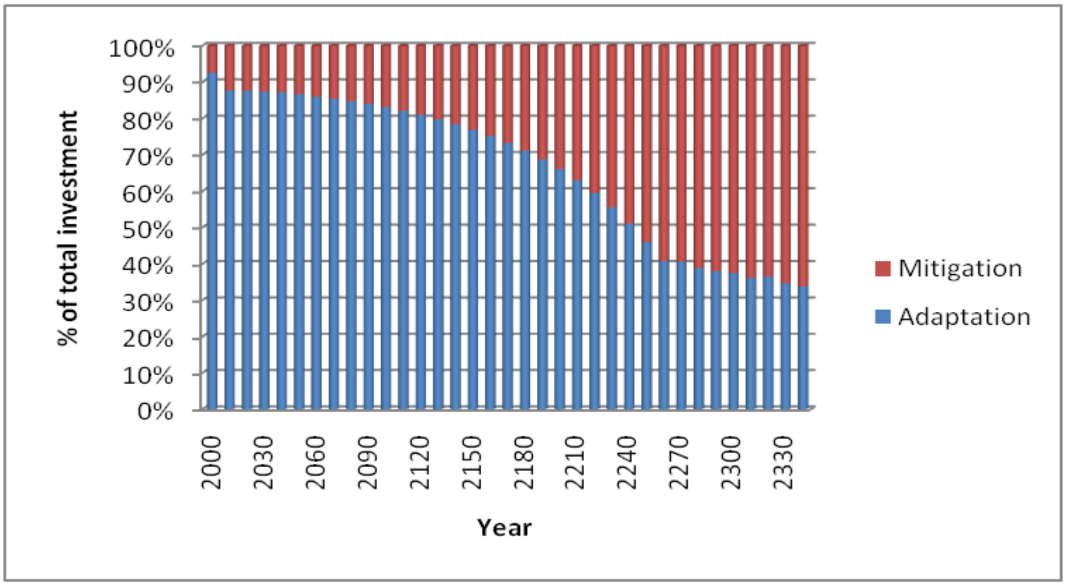

Figure 10. Temporal investment (percentage) of planned adaptation and mitigation.

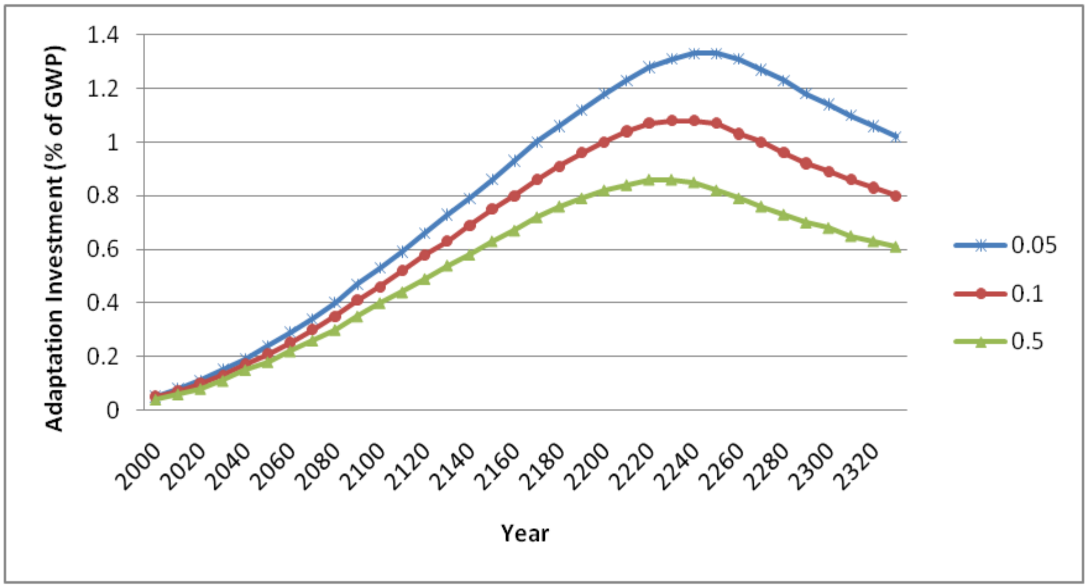

Figure 11. Adaptation investment with different depreciation rates.

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[i] Bosello suggests that fast-start investment should prioritize aggressive mitigation while adaptation prevails afterward.