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## Summary

It is often claimed that mitigation of greenhouse gases and adaptation to climate change are complementary strategies for dealing with climate change. If all that is meant by this is that it will usually be optimal to use both mitigation and adaptation to combat climate change, and that an increase in the perceived damages from climate change should lead to an increase in both mitigation and adaptation, then economic analysis supports this interpretation. But economic analysis has a more precise definition of complementarity: that reducing the costs of mitigation, say, will lead to more mitigation and hence more adaptation. However it turns out to be quite difficult to reproduce this result in the simple economic models that are used for the analysis of economic policy towards climate change. We show that only in the case where the effects of mitigation on marginal adaptation cost is strong do we get that increasing mitigation costs will reduce both mitigation and adaptation. The interpretation is that lowering the costs of mitigation increases mitigation, which slows climate change and makes adaptation more effective. Here mitigation and adaptation would be complements.

We use simple models of a single social planner who can choose the optimal mix of adaptation and mitigation to minimize total social costs. We proceed from a very basic model in which there is only one time period and no uncertainty, so there is a known relationship which shows how mitigation and adaptation reduce the damage costs caused by climate change, and known costs of adaptation and of mitigation. It is straightforward to show that in general the optimal combination of mitigation and adaptation will require the use of both strategies and that increasing damage costs requires an increase in both adaptation and mitigation, but that the two strategies are substitutes in the sense used by economists reducing the cost of mitigation increases the use of mitigation and reduces the use of adaptation.

We then extend the simple model to allow for a number of complicating features, including dynamics, multiple decision makers, and uncertainty, but it remains the case that mitigation and adaptation are substitutes. Only when we link the cost of adaptation to the level of mitigation do we find the possibility of complementarity.

This paper provides details of models used to support the arguments made in our survey paper, Ingham, Ma and Ulph (2005), *How do the costs of adaptation affect optimal mitigation when there is uncertainty, irreversibility and learning*.

# 1 Introduction

It is often claimed that mitigation of greenhouse gases and adaptation to climate change are complementary strategies to deal with climate change.[1] If what is meant by this is that it will usually be optimal to use both mitigation and adaptation to deal with climate change , and that a perceived increase in the damages caused by climate change should require an increase in both mitigation and adaptation, then simple economic analysis would support such an interpretation. But complementarity has a more technical meaning in economics, which would imply that if, say, the costs of mitigation fell, the optimal response would be to increase the level of mitigation and also adaptation. Simple economic analysis does not support such an interpretation. In almost all simple economic models of climate change mitigation and adaptation are substitutes: a reduction in, say, the cost of mitigation should lead society to do more mitigation and less adaptation.

In this paper, which provides the technical modelling that supports the arguments we made in our survey paper, Ingham, Ma and Ulph (2005), we develop a range of economic models to explore the relationship between mitigation and adaptation. We proceed from a very basic model in which there is only one time period, and no uncertainty, so there is a known relationship, which shows how mitigation and adaptation reduce the damage costs caused by climate change. A single social planner can choose the optimal mix of adaptation and mitigation to minimize total social costs. It is straightforward to show that in general the optimal combination of mitigation and adaptation will require the use of both strategies, and that the two strategies are substitutes, in a sense defined above

We extend the model, assumption by assumption, to see if and when the conclusion, that mitigation and adaptation are substitutes, changes. The first extension is to several agents; this is done in section 3. This arises from concern for the different spatial aspects of mitigation and adaptation, with mitigation dealing with a global public good, while adaptation often provides purely local benefits. We show that this has the obvious implication that if we move away from the assumption of a single social planner (who would have to be a global government of some type) and recognize that individual nation states may set their adaptation and mitigation policies independently then the noncooperative outcome will involve each state setting too little mitigation and too much adaptation, relative to the case of a single global social planner. This again reflects the fact that adaptation and mitigation are formally substitutes for each other. Then we extend the model to two periods in section 4. Mitigation and adaptation also differ in their temporal aspects in that the effects of mitigation in one period will produce benefits for all future periods while adaptation is often thought to produce benefits only for the period in which adaptation takes place. However while this may be true, a forward looking social planner will want to choose time paths for both mitigation and adaptation which are optimal,

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[1] See IPCC (1996), Pielke (1998).

and in a broad sense all the results for the static model carry over to a dynamic model, including the notion that mitigation and adaptation are substitutes. Then we consider in section 5 whether making adaptation costs depend on the amount of mitigation makes a difference, and show that this can allow for the possibility of a complementary relationship in the precise economic sense.

In all of sections 2 to 5 the models considered are ones of certainty. Section 6 considers a model which includes uncertainty. It is straightforward to show that if one introduces an exogenous risk of climate change damages into the simple models of the previous sections, then the main results go through in a straightforward way: an increase in the risk of climate change will cause the optimal levels of mitigation and adaptation to rise, but adaptation and mitigation remain substitutes. So we then look at introducing uncertainty as an endogenous factor. This is done by using a simplified version of the Kane-Shogren (2000) model. They obtain slightly different results by using a static model in which adaptation and mitigation play asymmetric roles: the level of damage costs can be reduced by adaptation, but mitigation reduces the risk of climate change, so risk is now endogenous. They show that an exogenous increase in risk has an ambiguous effect - it always leads to an increase in adaptation but the effect on mitigation depends on whether an exogenous increase in risk causes an increase or decrease in the marginal effectiveness of mitigation in reducing risk, and they give examples of how this effect could go either way.

## 2 Single Time Period, No Uncertainty, Single Social Planner

We consider a model of climate change in which the costs of climate change depend on how much we either mitigate or adapt. But mitigation and adaptation both also incur costs, and we set out below a simple model of the specification of this.

Let $m$ be the level of mitigation, $a$ be the level of adaptation. Total damage costs from Climate Change are $\delta D(m,a)$ where $\delta$ is a parameter affecting the severity of damage costs[2]. We make the following assumptions about damage costs. The first four are those for concavity of the damage function. Assumption A1.5 ensures that we obtain appropriate comparative static results

$$D_1 < 0, D_2 < 0. \tag{A1.1}$$

$$D_{11} > 0, D_{22} > 0. \tag{A1.2}$$

$$D_{12} = D_{21} \geq 0. \tag{A1.3}$$

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[2] In this specification of the problem, one factor which could affect the severity of damage costs is the level of Business-as-Usual emissions, i.e. emissions when both $m$ and $a$ are zero.

$$\min\{D_{11}, D_{22}\} \geq D_{12}. \tag{A1.4}$$

$$\left|\frac{D_{22}}{D_2}\right| > \left|\frac{D_{12}}{D_1}\right|, \ \left|\frac{D_{11}}{D_1}\right| > \left|\frac{D_{21}}{D_2}\right|. \tag{A1.5}$$

A1.1 says simply that increasing mitigation or adaptation reduces damage costs, while A1.2 says that there are diminishing returns to mitigation and adaptation. A1.3 says that increasing adaptation reduces in absolute terms the marginal reduction in damage by the last unit of mitigation and *vice versa*. A1.4 and A1.5 simply say that the own effects of an increase in mitigation and adaptation have a bigger effect on own marginal reduction in damage costs than the cross effects both in absolute (A1.4) and in relative terms (A1.5).

We denote by $M(m)$ total mitigation costs, and $A(a; \alpha)$ total adaptation costs, where $\alpha$ is a parameter reflecting how costly it is to carry out adaptation. We assume that mitigation and adaptation costs are strictly convex.

$$M' > 0, \ M'' > 0, \ A' > 0, \ A'' > 0$$

The social planner's problem is to choose $m$ and $a$ to minimize total costs arising from climate change damage costs, adaptation costs, and mitigation costs

$$C(m, a \mid \delta, \alpha) \equiv \delta D(m, a) + M(m) + \alpha A(a).$$

For which the first order conditions are

$$C_1 \equiv \delta D_1 + M' = 0, \tag{1}$$

$$C_2 \equiv \delta D_2 + \alpha A' = 0. \tag{2}$$

These are just the usual conditions that marginal costs of mitigation should equal saving in reduced damage cost from mitigation, and similarly for adaptation. Denote the optimal solution to the cost minimization problem by $m^*(\delta, \alpha)$ and $a^*(\delta, \alpha)$.

We now turn to comparative statics of how $m^*$and $a^*$ change as $\delta$ and $\alpha$ vary.[3] Consider first the effect of an increase in damage costs, represented by an increase in $\delta$. Then

$$\frac{\partial m^*}{\partial \delta} = \frac{C_{12}C_{2\delta} - C_{22}C_{1\delta}}{\Delta}, \tag{3}$$

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[3] Notice that $C_{11} = \delta D_{11} + M'' > 0$, $C_{22} = \delta D_{22} + \alpha A'' > 0$.
Finally note that

$$C_{1\delta} = D_1 < 0, \ C_{2\delta} = D_2 < 0,$$

$$C_{1\alpha} = 0, \ C_{2\alpha} = A' > 0.$$

$$\frac{\partial a^*}{\partial \delta} = \frac{C_{21}C_{1\delta} - C_{11}C_{2\delta}}{\Delta}. \tag{4}$$

where

$$\Delta = C_{11}C_{22} - C_{12}C_{21}.$$

We have $\Delta > 0$ by A1.2, A1.4, and the assumptions on $M$ and $A$.

By A1.5, it is straightforward to show that $\frac{\partial m^*}{\partial \delta} > 0$, $\frac{\partial a^*}{\partial \delta} > 0$. So an increase in damage costs increases both mitigation and adaptation.

Now come to the effect of an increase in adaptation costs, represented by an increase in $\alpha$. Then we will have since $C_{12} = \delta D_{12}$, and $D_{11} > 0$, $D_{12} \geq 0$

$$\frac{\partial m^*}{\partial \alpha} = \frac{C_{12}A'}{\Delta} > 0, \tag{5}$$

$$\frac{\partial a^*}{\partial \alpha} = -\frac{C_{11}A'}{\Delta} < 0 \tag{6}$$

So making adaptation more expensive reduces the amount of adaptation and increases the amount of mitigation. In this sense, *adaptation and mitigation are substitutes.* This follows from the assumption on the damage cost function that an increase in mitigation, say, reduces the marginal reduction in damages that can be achieved by the marginal unit of adaptation.

Of course, this model is extremely simple and it is worth noting a number of ways in which the result may not be robust before extending the model in more substantial ways.

**(a)** In the above analysis we assume an interior solution and this will certainly be the case if

$$\delta D_1(0,\cdot) < 0,\ M'(0) = 0,\ \delta D_2(\cdot,0) < 0,\ \alpha A'(0) = 0,$$

as is often assumed (i.e. at first, the cost of mitigation or adaptation is effectively costless). Of course if $M'(0) > \delta D_1(0, a^*)$ then it is optimal only to adapt, when $\alpha A'(0) > \delta D_2(m^*, 0)$ it is optimal only to mitigate. However, whilst these corner solutions are theoretically possible, they do not seem to be empirically relevant.

**(b)** The model assumes that Assumption 1 holds, which ensures that there is a unique solution to the first order conditions and that the comparative statics exercise is appropriate. It is possible that damage costs are not as well behaved as this, and that there are significant non-convexities. It is well known that such non-convexities pose difficulties for the conventional analysis of optimal externality policies (see Dasgupta and Mäler (2003)) and the problem of Thermohaline circulation may be just such an issue of non-convexities (though related to dynamics). For the purposes of this survey, we shall continue to assume that the second derivatives of the damage cost function have the signs shown in Assumption 1.

**(c)** The model is a very simple partial equilibrium model, and it is well known that goods or activities which are substitutes in partial equilibrium analysis may not be substitutes in a general equilibrium analysis. Thus increasing mitigation may affect other prices in the economy, especially factor prices, which could cause the costs of adaptation to fall. So, increasing mitigation of emissions could cause energy prices to fall causing some forms of adaptation which uses energy intensively (e.g. Air Conditioning) to become cheaper and so more use is made of adaptation, so making adaptation and mitigation complements at the general equilibrium level. We are not aware that such general equilibrium effects are strong enough to overturn the conclusion of the simple model that mitigation and adaptation are substitutes.

**(d)** There is a slightly different aspect to the previous example. Suppose that we ignore general equilibrium effects. Nevertheless the kind of link between adaptation and mitigation is sometimes suggested to possibly cause the problem of "*maladaptation*"[4]. Suppose one form of adaptation requires use of energy (e.g. Air Conditioning), is it possible that the additional emissions caused by use of air conditioning could cause additional damage sufficient to outweigh the direct adaptation benefit of using Air Conditioning?[5] To examine this in the context of the model, suppose that the damage function is written as:

$$\delta D(m - \mu(a), a),$$

where $\mu(a)$ captures offsets to mitigation caused by the use of a particular adaptation strategy.

The first order conditions are:

$$\delta D_1 + M' = 0, \tag{7}$$

$$\delta D_2 - \delta D_1 \mu' + \alpha A' = 0. \tag{8}$$

Now suppose that $\alpha A$ captures all of the direct cost of the adaptation strategy, including the cost of any energy used by the adaptation strategy, but excluding the social cost of the emissions generated by the adaptation. Then from (8) it is possible that

$$\delta D_2(e^*, 0) > \alpha A'(0),$$

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[4] This has been recognised as a problem for a very long time. For example, Huntington (1917) discusses climate change in the context of the decline of the Roman Empire and suggests that changes in rainfall patterns led to changes in agricultural practices that exacerbated those.

[5] Other possible causes of maladaptation are through competition for resources between mitigation and facilitative adaptation, Tol (2003), international trade effects on health in developing countries, Babiker *et al.* (2000). Scheraga and Grambsch (1998) refer to maladaptation due to suboptimal private decisions, but this is more a case of mal-regulation.

so it looks as if it is privately desirable to use the adaptation strategy based on the marginal costs at zero level of adaptation.

But it may also be true that

$$\delta D_2(e^*, 0) < |\delta D_1(e^*, 0)\mu'(0)| + \alpha A'(0),$$

so that when one takes account of the damage cost of the extra emissions, it would not be worth using the adaptation strategy, again at zero level of adaptation based on marginal costs but now including the social costs of the adaptation strategy.

So it looks as if there is potential maladaptation. However, this results from assuming that the damage cost of the emissions, which will arise from the adaptation emissions, have not been factored into the private costs of adaptation. But provided mitigation is optimally regulated, at the adaptation stage we do not need to factor into the adaptation costs the social costs of adaptation emissions because these will have been taken account of in the mitigation strategy. So, it should not be the case that the social costs of the additional emissions, associated with adaptation, have to be reflected in the user cost of adaptation. This is a case of an optimal corner solution where adaptation is not employed. It reflects again the fact that mitigation and adaptation need to be jointly determined.

# 3 Multi-Agents

Although the formal model is written down as the problem of a social planner choosing optimal regulation of adaptation and mitigation it is worth asking how such optimal policies could be implemented. Implicit in the discussion in part (d) is an important distinction sometimes made between mitigation and adaptation, namely that mitigation will call for some form of government regulation to reflect the problems of externalities and the public good nature of mitigation, whilst the adaptation decision can be "decentralized", i.e. left to individual agents to weigh the costs and benefits of adapting. We have argued in part (d) that this remains the case as long as mitigation is optimally regulated. But there is another important aspect of this public good/private good distinction. For mitigation is a global public good activity since what affects the damage on any one country is the global level of mitigation. However it is reasonable to suppose that adaptation is a private benefit – as each country's adaptation affects only that country.[6] We can capture this distinction by supposing that there are $N$ countries, $i = 1, ..., N$, where for country $i$ the appropriate cost function is

$$C^i(M_1, ..., M_N, a_i \mid \delta_i, \alpha_i) \equiv \delta_i D^i\left(\sum_{j=1}^N m_j, a_i\right) + M^i(m_i) + \alpha_i A^i(a_i).$$

We can then distinguish formal outcomes where the countries act non-cooperatively (i.e. no Climate Change Protocol) and where they act cooperatively (i.e. a globally binding agreement). The first order conditions for the two cases are

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[6] See Hanemann (2000), Kane and Shogren (2000), Mendelson (2000), Klein *et al.* (2003).

- Non-Cooperative:

$$\delta_i D_1^i + M^{i'} = 0, \tag{9}$$

$$\delta_i D_2^i + \alpha_i A^{i'} = 0. \tag{10}$$

- Cooperative:

$$\sum_j \delta_j D_1^j + M^{i'} = 0, \tag{11}$$

$$\delta_i D_2^i + \alpha_i A^{i'} = 0. \tag{12}$$

(9) and (10) are just the analogue of (1) and (2) for each country, and says that each country will choose to mitigate at the point where the marginal cost of an additional unit of mitigation equals its own private benefit from mitigation, and similarly for adaptation. The difference in (11) and (12) is that in the mitigation decision what is relevant for each country is the marginal reduction in global damage costs from an extra unit of mitigation. If we denote the optimal solution to the non-cooperative case by $(m_i^N, a_i^N)$ and to the cooperative case by $(m_i^C, a_i^C)$, then it is straightforward to see that $\sum m_i^N < \sum m_i^C$, so there will be too little global mitigation if countries do not cooperate – the standard free-rider problem. Although (10) and (12) look the same, because the level of mitigation will be different, it is straightforward to see that $a_i^N > a_i^C$. So the failure to get global agreement on mitigation means that there will be too little mitigation, and countries respond by carrying out too much adaptation.

Of course, it must be clear that the fact that countries increase adaptation from $a_i^C$ to $a_i^N$ where there is a failure to reach an international agreement does not mean that this adaptation response is imposing additional costs on countries compared to what they would face if they left adaptation at level $a_i^N$. Because the move from $a_i^C$ to $a_i^N$ is the best response of each country to the failure to agree on mitigation. If countries just left adaptation at levels $a_i^C$ they would be even worse off if there is no agreement on mitigation, because they would incur even greater damage costs.

# 4 Two-Period Models, No Uncertainty

An obvious weakness of the previous model is that it lacks any dynamic features, and climate change is inherently dynamic.[7] Here we extend the model in the simplest

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[7] For example, Klein *et al.* (2003) discuss the different temporal aspects of mitigation and adaptation.

possible way to allow for dynamics to see what differences this makes to the previous conclusions. Suppose now that there are two time periods, $t = 1, 2$, and mitigation and adaptation in period $t$ are denoted by $m_t$, $a_t$. Damages occur at the end of period 2, and depend on cumulative mitigation $m = m_1 + m_2$, and cumulative adaptation $a = a_1 + a_2$, and are $\delta D(m, a)$. Costs of mitigation and adaptation in period $t$ are given by $M_t(m_t)$, $\alpha_t A_t(a_t)$. For simplicity we shall ignore any depreciation to the stock of mitigation and adaptation and also discounting.

The social planner now chooses $m_t$, $a_t$ to minimize in period 2,

$$C^2(m_1, m_2, a_1, a_2 \mid \delta, \alpha_2) \equiv \delta D(m, a) + M_2(m_2) + \alpha_2 A_2(a_2)$$

with first order conditions

$$C_1^2 \equiv \delta D_1 + M_2' = 0, \tag{13}$$

$$C_2^2 \equiv \delta D_2 + \alpha_2 A_2' = 0. \tag{14}$$

These are just the analogue of (1) and (2) for the one period problem. Denoting the solution by $m_2^*(m_1, a_1, \delta, \alpha_2)$, $a_2^*(m_1, a_1, \delta, \alpha_2)$, we have the normal results

$$\frac{\partial m_2^*}{\partial \delta} > 0,\ \frac{\partial m_2^*}{\partial \alpha_2} > 0,\ \frac{\partial a_2^*}{\partial \delta} > 0,\ \frac{\partial a_2^*}{\partial \alpha_2} < 0.$$

Turning to the effects of a change in first period mitigation and adaptation, note that

$$C_{1m_1}^2 = \delta D_{11} > 0,\ C_{2m_1}^2 = \delta D_{21} \geq 0,$$

$$C_{1a_1}^2 = \delta D_{12} \geq 0,\ C_{2a_1}^2 = \delta D_{22} > 0.$$

$$\Delta^2 = C_{11}^2 C_{22}^2 - C_{12}^2 C_{21}^2 > 0,$$

It is straightforward to show that

$$\frac{\partial m_2^*}{\partial m_1} = -1 + M_2'' \frac{(\delta D_{22} + \alpha_2 A_2'')}{\Delta^2},$$

so $-1 < \frac{\partial m_2^*}{\partial m_1} < 0$.

$$\frac{\partial a_2^*}{\partial m_1} = -\frac{\delta D_{21} M_2''}{\Delta^2},$$

so $-1 < \frac{\partial a_2^*}{\partial m_1} < 0$, and $-1 < \frac{\partial m_2^*}{\partial m_1} + \frac{\partial a_2^*}{\partial m_1} < 0$.

So increasing mitigation by 1 unit in period 1 reduces mitigation and adaptation in period 2, but by less than 1 unit in total. Similar results apply for an increase in adaptation of 1 unit, $-1 < \frac{\partial m_2^*}{\partial a_1} + \frac{\partial a_2^*}{\partial a_1} < 0$.

Let

$$C^{2*}(m_1, a_1, \delta, \alpha_2) \equiv \delta D(m_1 + m_2^*, a_1 + a_2^*) + M_2(m_2^*) + \alpha_2 A_2(a_2^*).$$

Turning to the first period, the problem of the social planner is determine $m_1$, $a_1$ to minimize

$$C^1 = C^{2*} + M_1(m_1) + \alpha_1 A_1(a_1).$$

For which the first order conditions are:

$$C_1^1 = C_1^{2*} + M_1' = \delta D_1 + M_1' = 0,$$

$$C_2^1 = C_2^{2*} + \alpha_1 A_1' = \delta D_2 + \alpha_1 A_1' = 0.$$

Let the solution to the above two equations be denoted by $m_1^*(\delta, \alpha_1, \alpha_2)$, $a_1^*(\delta, \alpha_1, \alpha_2)$.

To assess the properties of these functions note that:

$$C_{11}^1 = \delta D_{11}\left(1 + \frac{\partial m_2^*}{\partial m_1}\right) + \delta D_{12}\frac{\partial a_2^*}{\partial m_1} + M_1'' > 0,$$

$$C_{12}^1 = \delta D_{11}\frac{\partial m_2^*}{\partial a_1} + \delta D_{12}\left(1 + \frac{\partial a_2^*}{\partial a_1}\right) > 0,$$

$$C_{21}^1 = \delta D_{21}\left(1 + \frac{\partial m_2^*}{\partial m_1}\right) + \delta D_{22}\frac{\partial a_2^*}{\partial m_1} > 0,$$

$$C_{22}^1 = \delta D_{21}\frac{\partial m_2^*}{\partial a_1} + \delta D_{22}\left(1 + \frac{\partial a_2^*}{\partial a_1}\right) + \alpha_1 A_1'' > 0,$$

$$\Delta^1 = C_{11}^1 C_{22}^1 - C_{12}^1 C_{21}^1 > 0,$$

$$C_{1\delta}^1 = D_1 + \delta D_{11}\frac{\partial m_2^*}{\partial \delta} + \delta D_{12}\frac{\partial a_2^*}{\partial \delta},$$

$$C_{2\delta}^1 = D_2 + \delta D_{21}\frac{\partial m_2^*}{\partial \delta} + \delta D_{22}\frac{\partial a_2^*}{\partial \delta},$$

$$C^1_{1\alpha_1} = 0,$$

$$C^1_{2\alpha_1} = A_1' > 0.$$

It is straightforward if tedious to show that

$$\frac{\partial m_1^*}{\partial \delta} > 0,\ \frac{\partial m_1^*}{\partial \alpha_1} > 0,\ \frac{\partial a_1^*}{\partial \delta} > 0,\ \frac{\partial a_1^*}{\partial \alpha_1} < 0.$$

So again the results for the one period model carry over. In summary, all the results from the one-period model carry over to the dynamic model.

Again a few comments about robustness are in order. These models assume damage costs occur only in the second period. In this sense we can think of adaptation in period 1 as being "pro-active" whilst adaptation in period 2 might be thought as "reactive". However, the results are robust to including damage costs in each time period, although in this case it is more difficult to distinguish between adaptation as reactive or pro-active. Adaptation in any one period will reflect both the damage that occurs in that period as a result of the current stock of greenhouse gas emissions (so clearly on past changes), but to the extent that current adaptation builds a stock of future adaptation capital it also helps to adapt to future climate change. Of course, part of this blurring just reflects the fact that we use a simple variable and it plays a stock and flow role.

Much of the flavor of these results also carries over if we extend the model to an infinite-horizon model. None of this should be very surprising. Even in the one-period model, using a single variable to capture "mitigation" and a single variable to capture "adaptation" is a gross simplification. There will be many forms of mitigation and adaptation. But if damages increase the general efficiency argument would suggest we should increase all forms of adaptation and mitigation while if all forms of adaptation become more expensive then we would expect to see less adaptation of all kinds and more mitigation of all kinds. Adaptation and mitigation in different time periods are just different ways of adapting and mitigating.

# 5 When Cost of Adaptation Depends on Amount of Mitigation

To get a more interesting outcome we need to introduce dynamic considerations in a more interesting way. One argument sometimes advanced is that adaptation may be harder to implement if the rate of change of climate is fast.[8] Now it is not clear what underlies this belief. Part of it might reflect issues to do with the ability to learn, but that cannot be captured in the model so far which assumes certainty. Partly this could

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[8] See IPCC (2001), Salathé (2003).

just reflect the fact that it takes time to accumulate a stock of adaptive capital – if one has many decades available then the costs of moving a coastal city inland will be relatively small compared to the costs of doing this within a few decades, essentially because the former can rely on the natural process of replacing obsolescent capital to achieve adaptation, whereas in the latter one has to retire capital early. This effect is already captured, albeit crudely, by assuming increasing cost of adding to the new stock of capital in any one period, so any increase in those costs will already be captured by the shift parameter $\alpha_i$. The increased difficulty of adaptation the faster the change in climate can also reflect problems for non-human agents where over time species might be able to migrate or mutate to adapt to climate change, but if it is too rapid they could be wiped out. However, what we are concerned with here is how the speed of climate change might affect human adaptation. Whatever the underlying explanation, a crude way of capturing this in our model might be to assume that in period 2 (we consider period 2 just for simplicity) the costs of adaptation also depend on the level of mitigation in period 2, with more mitigation in period 2 (slower rate of change of climate in period 2) reducing the cost of adaptation. So we could write adaptation costs in period 2 as

$$A^2(a_2, m_2),\ with\ A_2^2 < 0,\ A_{22}^2 > 0,\ A_{12}^2 < 0,$$

so more mitigation reduces both total and marginal costs of adaptation. For simplicity we put the cost shift parameter onto the mitigation cost. Then the period 2 problem can now be written as choose $m_2$, $a_2$ to minimize

$$\widehat{C}^2 \equiv \delta D(m, a) + \mu M^2(m_2) + A^2(a_2, m_2),$$

with first order conditions:

$$\widehat{C}_1^2 \equiv \delta D_1 + \mu M^{2'} + A_2^2 = 0,$$

$$\widehat{C}_2^2 \equiv \delta D_2 + A_1^2 = 0.$$

Now

$$\widehat{C}_{11}^2 = \delta D_{11} + \mu M^{2''} + A_{22}^2 > 0,$$

$$\widehat{C}_{22}^2 = \delta D_{22} + A_{12}^2 > 0,$$

$$\widehat{\Delta}^2 = \widehat{C}_{11}^2 \widehat{C}_{22}^2 - \left(\widehat{C}_{12}^2\right)^2,$$

$$\widehat{C}_{1\mu}^2 = M_2' > 0,$$

$$\widehat{C}_{2\mu}^{2} = 0,$$

But as $A_{12}^{2} < 0$, $D_{12} \geq 0$.we are unable to definitely sign

$$\widehat{C}_{12}^{2} = \delta D_{12} + A_{12}^{2},$$

so as

$$\frac{\partial m_2^*}{\partial \mu} = -\frac{\widehat{C}_{22}^{2}\widehat{C}_{1\mu}^{2}}{\widehat{\Delta}^2} < 0,$$

$$\frac{\partial a_2^*}{\partial \mu} = \frac{\widehat{C}_{21}^{2}\widehat{C}_{1\mu}^{2}}{\widehat{\Delta}^2},$$

then

$$sign\left(\frac{\partial a_2^*}{\partial \mu}\right) = sign\left(\widehat{C}_{21}^{2}\right).$$

which may be positive or negative depending on the relative magnitudes of $A_{12}^{2}$ and $D_{12}$.

So if the effects of mitigation on marginal adaptation cost is strong enough, mitigation leads to lower marginal damage costs from adaptation, so $\widehat{C}_{21}^{2} < 0$, hence increasing mitigation costs will reduce both mitigation and adaptation.

The conclusion is obvious – lowering costs of mitigation increases mitigation which slows Climate Change and makes adaptation more effective. So now mitigation and adaptation would be complements.

# 6 Endogenising Risk

We now allow for uncertainty about damage costs. Let $\pi$ be the probability of positive damage costs, $1 - \pi$ the probability of no damage costs. We assume that $\pi$ depends on a parameter, $\rho$. In this section we also allow for $\pi$ to depend endogenously on the level of mitigation. This yields a model similar to the previous section but with endogenous risk along the lines suggested by Kane and Shogren (2000). However mitigation only affects the probability of damage and not its level which depends solely on the amount of adaptation. The analysis provided here shows that we obtain the same general conclusion that mitigation and adaptation will be substitutes, and so that our result from the previous section is robust to extension to endogenous probability.

The objective function is now as follows:

$$\min_{\{m,a\}} \pi(\rho, m) D(a) + M(m) + \alpha A(a),$$

where we have $\frac{\partial \pi}{\partial m} < 0$, $\frac{\partial \pi}{\partial \rho} > 0$, $\frac{\partial^2 \pi}{\partial m^2} > 0$, and $\frac{\partial^2 \pi}{\partial \rho \partial m} < 0$; $D' < 0$, $D'' > 0$, $A' > 0$, $A'' > 0$ $M' > 0$, $M'' > 0$.

The first order conditions which determine the optimal mix of mitigation and adaptation are as follows:

$$M' + \frac{\partial \pi}{\partial m} D = 0. \tag{15}$$

$$\alpha A' + \pi(\rho, m) D' = 0 \tag{16}$$

Next we do comparative statics analysis. First the first order conditions differentiate with respect to $\rho$, we have

$$z_1 \frac{\partial a}{\partial \rho} + z_2 \frac{\partial m}{\partial \rho} = -\frac{\partial \pi}{\partial \rho} D',$$

$$z_3 \frac{\partial a}{\partial \rho} + z_4 \frac{\partial m}{\partial \rho} = -\frac{\partial^2 \pi}{\partial \rho \partial m} D,$$

where we have $z_1 = \pi D'' + \alpha A'' > 0$, $z_2 = z_3 = \frac{\partial \pi}{\partial m} D' > 0$, $z_4 = \frac{\partial^2 \pi}{\partial m^2} D + M'' > 0$, and $\Delta = z_1 z_4 - z_2 z_3 > 0$. It proves that

$$\frac{\partial a}{\partial \rho} = \frac{1}{\Delta} \left[ z_4 \left( -\frac{\partial \pi}{\partial \rho} D' \right) + z_2 \left( \frac{\partial^2 \pi}{\partial \rho \partial m} D \right) \right],$$

$$\frac{\partial m}{\partial \rho} = \frac{1}{\Delta} \left[ z_1 \left( -\frac{\partial^2 \pi}{\partial \rho \partial m} D \right) + z_3 \left( \frac{\partial \pi}{\partial \rho} D' \right) \right].$$

So we obtain the result that if the "cross effects" are negligible, i.e., $z_2 = z_3 = 0$, then $\frac{\partial a}{\partial \rho} > 0$, and $\frac{\partial m}{\partial \rho} > 0$, so increasing risk of damages increases both mitigation and adaptation.

Next differentiating the first order conditions with respect to $\alpha$, we have

$$z_1 \frac{\partial a}{\partial \alpha} + z_2 \frac{\partial m}{\partial \alpha} = -A',$$

$$z_3 \frac{\partial a}{\partial \alpha} + z_4 \frac{\partial m}{\partial \alpha} = 0,$$

This proves that

$$\frac{\partial a}{\partial \alpha} = -\frac{1}{\Delta} z_4 A' < 0,$$

$$\frac{\partial m}{\partial \alpha} = \frac{1}{\Delta} z_3 A' > 0.$$

and so that we have the result that mitigation and adaptation are substitutes. which is what we obtained in section 1.

# 7 Conclusions

In general, we show that adaptation and mitigation will be substitutes. This just reflects the rather mild assumption that an increase in mitigation reduces the marginal reduction in damage costs that can be achieved by adaptation. When is it possible for complementarity to occur? We found that it is possible for such complementarity in the case that adaptation costs depend on the amount of mitigation. The case of maladaptation is often suggested as another reason why mitigation and adaptation could be complements. However, it is only possible if there were sub-optimal policies in other parts of the economy, and a clear policy recommendation emerges that the causes of this sub-optimality should be removed. But clearly, special requirements may be needed for this to happen.

The fact that adaptation and mitigation will be substitutes confirms the view of Kane and Yohe (2000) and Parry *et al.* (2000) that we need to have an integrated approach to adaptation and mitigation, and we cannot rely on either mitigation alone or adaptation alone to deal with climate change. This result does not change if we introduce endogenous risk into the model. It only changes when we make the adaptation cost depend on the amount of mitigation.

Only in the case where the effects of mitigation on marginal adaptation cost is strong do we get that increasing mitigation costs will reduce both mitigation and adaptation. So that lowering the costs of mitigation increases mitigation which slows Climate Change and makes adaptation more effective. Here mitigation and adaptation would be complements.

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