EFFICIENT ADAPTATION TO CLIMATE CHANGE

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Abstract. Firms and individuals will likely engage in substantial private adaptation with respect to climate change in such sectors as farming, energy, timber, and recreation because it is in their interest to do so. The shared benefit nature of joint adaptation, however, will cause individuals to underprovide joint adaptation in such areas as water control, sea walls, and ecological management. Governments need to start thinking about joint adaptation, being careful to design efficient responses which treat climate change problems as they arise.

1. Introduction

If no action is undertaken, greenhouse gases are expected to continue to accumulate for decades leading to future changes in climate (Houghton et al., 1996). Even with aggressive policies to begin to curb emissions, greenhouse gases are nonetheless expected to continue to grow (Houghton et al., 1996). Whether the world's governments settle on strict abatement policies or no policies at all, one issue every country in the world must face is how to adapt to the future changes in climate that will occur. There are many adaptations that can be undertaken in response to climate change as seen in Table I. The damages from climate change in virtually every sector, both market and nonmarket, can be reduced by appropriate responses. Adaptation is consequently one of the important links between an initial environmental change and the final consequences to society. Adaptation (including its costs) must consequently be taken into account in order to design efficient climate change policies.

Several authors have begun to address adaptation and have made several important contributions to date. First, adaptation will reduce damages (see Table II). For example, agronomic studies of agriculture in the United States reveal that efficient adaptation will reduce damages from climate change (Easterling et al., 1993; Kaiser et al., 1993; Adams et al., 1998). Cross-sectional studies of agriculture using the Ricardian method suggest a similar result (Mendelsohn et al., 1994, 1996; Kumar and Parikh, 1998a; Sanghi et al., 1998). Studies on climate change effects on other sectors of the United States economy also reveal the importance of adaptation (Mendelsohn and Neumann, 1998). Second, some adaptations are ex-post, they can be undertaken after climate has changed whereas other adaptations are ex-ante, they require an ability to anticipate and forecast climate (Goklany, 1995;

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TABLE I
Market sector adaptations to climate change

Sector	Private/ public	Adaptation
Agriculture	Private	Alter crop species
		Alter timing
		Irrigation
	Public	Plant breeding
Sea level rise	Private	Depreciate vulnerable buildings
	Public	Sea walls as needed
		Beach enrichment
Forestry	Private	Harvest vulnerable trees
		Plant new trees
		Intensify management
Energy	Private	New cooling capacity
		Changes in insulation
		Cool building designs
	Public	New building codes
Water	Private	Invest into water efficiency
	Public	Shift water to high value uses
		Divert/store more water
		Flood zoning
Biodiversity	Public	Move endangered species
		Manage landscapes
		Plant adapted species
Health	Private	Prepare for extreme weather
		Avoid insect bites
	Public	Control disease carriers
		Treat infected people
		Control diseased ecosystems
Aesthetics	Private	Adapt behavior (e.g., recreation)
	Public	Educate public of adaptive options

TABLE II
Effectiveness of adaptation

Country	Sector	Net impact W/O adaptation	Net impact W adaptation
U.S.	Farm	–$8 to –$18 billion (Bruce et al., 1996)	+$3 to –$11 billion (Mendelsohn et al., 1994)
U.S.	Coasts	–$6 to –$12 billion (Bruce et al., 1996)	–$0.1 to –$0.6 billion (Yohe et al., 1996)
India	Farm	–$3 to –$4 billion (Kumar and Parikh, 1998a)	–$1.4 to –$2.4 billion (Sanghi et al., 1998) (Kumar and Parikh, 1998b)

Fankhauser et al., 1999; Smith and Lenhart, 1996; Tol et al., 1998). Although it is easy to believe that ex-post adaptations will be undertaken, it is less clear whether ex-ante efforts will be widespread.

This paper stresses two additional points. First, that there is an efficient amount of adaptation. Adaptation is efficient only if the cost of making the effort is less than the resulting benefits. We argue that public policy should encourage efficient adaptation. The impact literature has generally not examined the efficiency of adaptation (Watson et al., 1996; Bruce et al., 1996). Many models of impacts were constructed that either ignored potential responses by both individuals and societies (e.g., ‘dumb farmer’ models) or introduced these responses in an *ad hoc* fashion (Rosenzweig and Parry, 1994). Although efficient adaptation responses can reduce the overall costs associated with climate change, inefficient responses can actually increase costs.

Second, it is important to distinguish between private adaptations done only for the benefit of the actor making the decision and joint adaptations where there are many beneficiaries. Self-interest will motivate most actors to engage in efficient private adaptation. The principle doubt about private adaptation concerns how widespread ex-ante efforts will be. Self-interest, however, will not lead to efficient levels of joint adaptation. Joint adaptation will be efficient only through government action. Further, political forces are likely to encourage even governments to engage in inefficient adaptation behavior. Thus, it is not at all clear whether efficient levels of joint adaptation will be undertaken.

In Section 2, we develop a formal static model of private adaptation. We examine when private adaptation will be efficient. In Section 3, we develop a static model of joint adaptation and explain why markets will underprovide this service. We then explore the hurdles that must be overcome for joint adaptation to be efficient. In Section 4, we extend these two models of adaptation to a dynamic setting. In capital intensive sectors, adaptation is a gradual process of investment and accelerated depreciation. We examine ex-ante versus ex-post adaptation in this context. We conclude with a general discussion of the importance of efficient adaptation to climate change.

2. Private Adaptation

Private adaptation is a behavioral response by an individual or a firm to an environmental change for one's own benefit. There are several examples of private adaptation listed in Table I in the agriculture, energy, recreation, and timber sectors. Adaptation is private if the decision-maker is the only beneficiary. With respect to climate change, adaptation can either take the form of reducing damages that would otherwise occur or taking advantage of new opportunities that climate change makes possible. To be efficient, the adaptation must maximize the net benefits to the individual. Because the individual receives the net benefits from engaging in private adaptation, people will tend to choose efficient levels of private adaptation.

Private adaptation is expected to occur in most climate sensitive sectors of the economy. We begin, then, with a simple model of an economic sector that is climate sensitive. Suppose that an individual or firm can engage in some expenditure that will tend to reduce the damages or increase the benefits from climate change. Let us define reduced damages and increased benefits in terms of a benefit function that depends upon the amount of adaptation, A, and the change in temperature, T:

$$B = f(A, T)\,, \tag{1}$$

where $dB/dA > 0$, $d^2B/dA^2 < 0$, $dB/dT > 0$, and $d^2B/dT^2 > 0$. Benefits are assumed to increase at a decreasing rate with adaptation. Potential benefits are greater with a larger change in temperature.

However, adaptation is rarely free. There is also a cost function associated with adaptation either from lost opportunities or explicit outlays. The cost function has the following properties:

$$C = g(A)\,, \tag{2}$$

where $dC/dA > 0$ and $d^2C/dA^2 > 0$. Cost rises with adaptation. There is no specific reason to believe that costs are also a function of the temperature change but this could be included if relevant.

The objective of the individual is to maximize net benefits. That is, the firm or person is assumed to choose a level of A which maximizes benefits minus costs:

$$\max_A B(A, T) - C(A)\,. \tag{3}$$

The first order conditions suggest choosing a level of A such that the marginal benefits equal the marginal costs:

$$MB = MC\,. \tag{4}$$

If the individual must pay all the costs and yet enjoys all the benefits, then it is in that person's direct interest to choose the optimal amount of adaptation. It is this result which gives economists such confidence that efficient adaptation will be selected for private adaptation.

Of course, if the assumptions of the above model are violated, efficient adaptation may not be selected. For example, if some of the costs of the adaptation are not paid by the individual, then the person may make the wrong choice. For example, what would happen if the government subsidizes adaptation by an amount, γ. Equation (3) will change to:

$$\max_A B(A,T) - (1-\gamma)C(A)\,. \tag{5}$$

The individual will choose an amount of adaptation that equilibrates marginal benefits with their share of costs:

$$MB = (1-\gamma)MC\,. \tag{6}$$

The result will be too much adaptation. Although it is individual rational behavior, the subsidy encourages the individual to invest more than the efficient amount.

An alternative example of incorrect costs occurs when there is an externality from an adaptation decision. For example, suppose that a forester switches tree species in order to take advantage of a warmer climate. Suppose that the forester only considers the timber benefits against the cost of encouraging the species switch. However, suppose that wildlife species dependent on the old species cannot survive with the new species in place. If the wildlife is valued by others, but the landowner does not consider this effect, the switch in species introduces an externality, $E(A,T)$, a cost which must be borne by others. The landowner will make the decision based only on his own costs and benefits (such as in (3)). However, society would face the following choice:

$$\max_A B(A,T) - C(A) - E(A,T)\,, \tag{7}$$

whereas the landowner would choose a level of adaptation that dealt with only the first two terms above as in (4), the optimal choice would now be:

$$MB = MC + ME\,. \tag{8}$$

The optimal choice would weigh the wildlife effect as well as the cost of the conversion against the benefits of the new species. The landowner, in this case, would be too eager to make the change. Private adaptation can be inefficient if it involves substantial externalities.

There is one other circumstance in which people may make poor decisions about private adaptation. If there is substantial uncertainty about the future benefits of adaptation but the current costs are reasonably clear, people may hesitate to make adaptation choices. This is especially clear with ex-ante decisions where the adaptation cost has to be invested far before the climate change materializes. Since there is likely to be great uncertainty about future benefits from current actions, people may hold back from choosing such adaptation options. In order to predict future benefits, the individual would have to be able to predict future climate change in her locality, understand what impacts this would have, and comprehend what actions could be taken to counteract these effects. Given that few experts exist in the world with this information, it is unreasonable to expect private citizens would be in command of this knowledge. It is probably realistic to assume that there will be limited ex-ante private adaptation.

It is also important to note that some climate changes will be more difficult to adapt to than others. The adaptations in Table I respond to changes in the mean temperatures and precipitation levels of seasons. If greenhouse gases increase the interannual variation of temperature, there is much less people can do to adjust to this change. The very cross-sectional studies that suggest farmers can readily adapt to changes in mean temperature, also suggest that farms are dramatically damaged by increases in interannual variance (Mendelsohn et al., 1996). With simple warming, farmers can plant more suitable crops, plant earlier, engage in double cropping, invest in irrigation, etc. However, if some years are now warmer whereas other years are now cooler, no single crop will be appropriate for all outcomes. With higher climate variance, farmers can plant portfolios of crops to protect against single large disasters but they cannot customize for a known outcome. Adaptations against increases in climate variance are difficult to identify and are likely to have only modest net benefits.

Another relevant distinction to make is between short run and long run adaptations. In the short run, capital is largely fixed and most of the available adjustments are limited to changes in behavior. In the long run, all capital is replaced. Changes in residential buildings, factories, and transportation systems can all be made relatively cheaply over the long run. If those same changes were made in the short run, vast amounts of existing capital would have to be prematurely abandoned. For example, suppose that warming encouraged people to shift to residences with less insulation, less heating capacity, and more cooling capacity. If this change were made suddenly, many homes would have to be retrofitted or abandoned before the useful life of their systems were over. The cost would be enormous. However, if this same change were made gradually over a long period of time so that people could make the change when they had to replace their furnace or buy a new air-conditioner anyway, the capital cost would be substantially less.

Perhaps the most controversial application of adaptation has been to farmers. It is easy to see that adaptation would have a large effect on the outcome of warming to farmers. Agronomists have long known that different crops prefer different climates. As shown in Figure 1, wheat tends to prefer cooler, dry environments, corn moderately warm, wet environments, and many fruits and vegetables prefer warmer settings. An examination of where different crops are grown in the United States reveals fruit and vegetables being grown in the southern tier of the U.S., corn

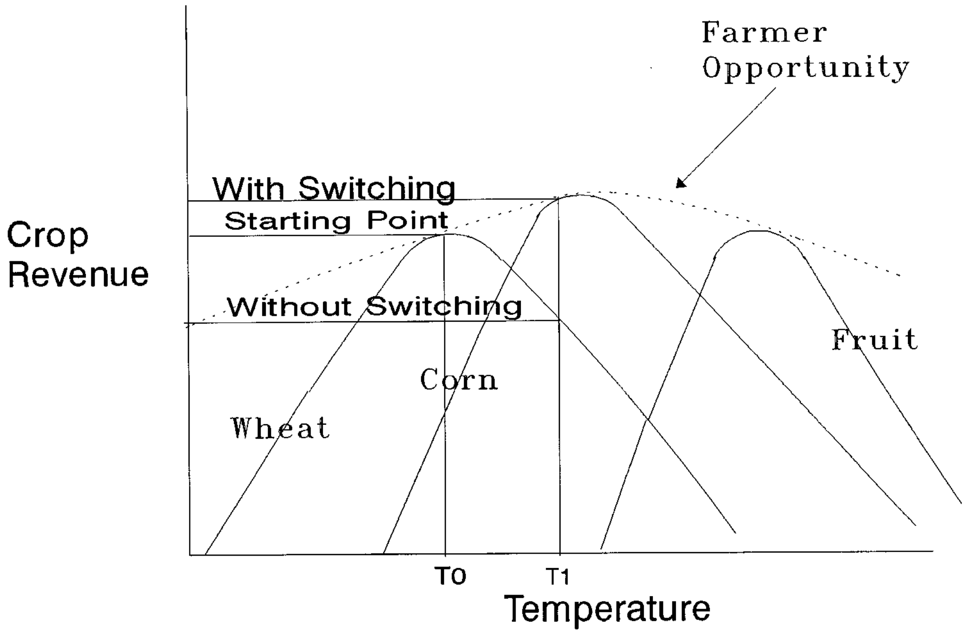

Figure 1. Crop choice adaptation.

in the Midwest, and wheat in the northern tier, western states. These choices reflect climate adaptation.

If climate were to change and become wetter and warmer, farmers would adjust their choices to fit the new conditions. Farms on the southern frontier of the wheat region might switch to corn. Farms on the southern frontier of the corn region could switch to fruits and vegetables. Farms in the warmest fruit and vegetable regions could look for subtropical crops. These efficient adaptations would reduce the damages that would otherwise take place. If farmers continued to grow the same crop even in the warmer climate, many of them could suffer large losses. However, by switching to crops more suitable to the new environment, farmers could lessen these potential damages and in some cases make themselves better off than before.

Of course, the situation with farming is even more complex than just a temperature and precipitation change. The principal manmade greenhouse gas, carbon dioxide, will also increase with changing climates. Higher carbon dioxide levels will increase crop productivity. The comparison of before and after must consequently take into account both the change in climate and the increased productivity from carbon fertilization. This complex comparison is drawn in Figure 2. The initial net revenue curve with respect to climate is displayed with the solid lines and the new productivity at the higher carbon dioxide levels is shown with dotted lines. Imagine a farmer who currently enjoys temperature T_0. This farmer will choose to grow wheat at income R_0 because that is the most profitable crop given initial conditions. Now, suppose warming drives his farm to temperature T_1.

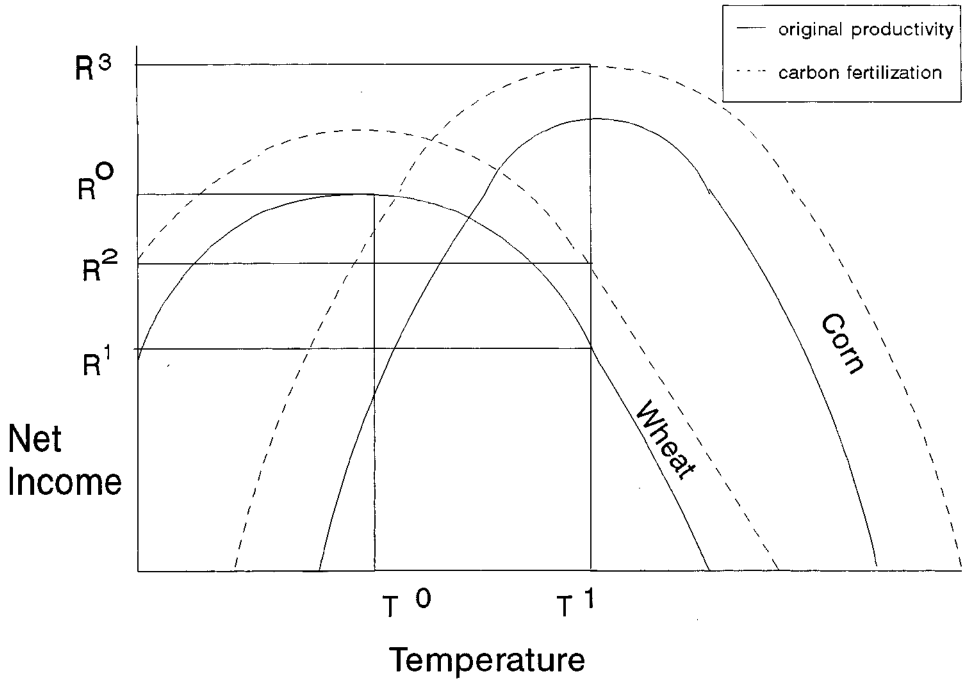

Figure 2. Crop choice with warming and carbon fertilization.

If the farmer continued to grow wheat, he would suffer a reduction in net income to R_2. Although carbon fertilization has helped mitigate some of the reduction in net revenue (which would otherwise have fallen to R_1), there is still a small loss from warming. Faced with this situation, the farmer could switch to corn and earn income R_3. The combination of carbon fertilization and adaptation turns climate change from a net damage to a net benefit for this farmer.

As long as the costs and rewards are borne by the decision-maker, private adaptation will tend to be efficient. Under these conditions, the private calculus and the social calculus are identical. The private decision-maker can be left to her own devices to make an efficient choice. No government policy is required to get private adaptation to be efficient.

Governments, however, could be helpful if there are externalities associated with an adaptation. Governments could subsidize desirable changes and regulate undesirable actions with important externalities. Governments could intervene in these circumstances to encourage individuals to incorporate the externalities into their decision making. If governments can demonstrate that private adaptations involve large new externalities, they should attempt to manage these situations efficiently.

A second justification for government action on private adaptation concerns information. As discussed above, some adaptations may require that decision-makers learn a substantial amount of information about future climates, their impacts, and possible adaptation options. The information costs could be too high for individuals to acquire. Governments could get involved in collecting and dispersing information about future climates. They could provide forecasts explaining how the weather is expected to change over time, who is likely to be affected, and what they could do to adjust. Such actions would seem especially justified with respect to ex-ante adaptations that need to be made well in advance of the actual climate change. For example, foresters might want to have long-range climate forecasts before they plant a long-lived tree. If future climates will be very different from current ones, the forester may well want to choose a different species.

A third justification for government involvement in private adaptation is equity. Although private adaptation is efficient, it may not be considered just. Private adaptation is paid by the victims. In many circumstances, society has stated that polluters should pay for the costs and damages from pollution (see, for example, Esty and Mendelsohn, 1998). Governments might get involved in private adaptation to shift the burden of the costs from the victims to the polluter. The equity argument seems especially powerful in an international context where climate change is currently being caused by relatively wealthy high-latitude countries and yet the victims may well be largely poorer low-latitude countries. The ideal solution, in this case, is for the polluters to give lump sum transfers of wealth to the victims. In practice, lump sum transfers are rarely given and what payments are made often do not reach the victims. Instead, it is far more likely that the polluters will engage in some form of subsidy or foreign aid program where the polluters control how the resources are spent. The danger, in this circumstance, is that the resources could be devoted to programs that provide benefits primarily to the polluters by purchasing desired foreign cooperation or by supporting favored contractors. Another drawback of equity programs is that the polluters are unlikely to care whether the resources are spent carefully, so that efficiency is not likely to be encouraged.

3. Joint Adaptation

Joint adaptation involves responses to climate impacts where there are many beneficiaries to each action. Joint adaptation resembles a ‘public good’ (Samuelson, 1954). Joint adaptation is not an aggregation of private adaptation responses. A group of farmers individually adapting to a warmer environment is still private adaptation because each farmer acts independently and each has a private reward for his action. The fact that all the farmers may choose to respond the same way does not make it joint adaptation. Adaptation is joint only when each action affects the benefits other individuals receive. For example, if people wish to respond to rising sea levels by building a sea wall, it is critical that all the property owners adjoining the sea build the wall. If some build the wall but others do not, all the properties will be flooded. The construction of the sea wall is a joint adaptation. In contrast, if the coastal owners respond by gradually letting their properties depreciate, this is a private response, since each owner can choose to depreciate his property independently of the other property owners and will be rewarded independently regardless of what the other owners do. Other examples of joint adaptation include health responses, biodiversity protection, and modifications of water supplies.

The general model of joint adaptation reveals that the benefits of actions are shared across more than one decision-maker:

$$\max \sum B_i(a_1, a_2, \ldots, a_n, T) - \sum C(a_i)\,, \tag{9}$$

where a_i is the amount of adaptation committed by individual i. With private adaptation, the benefits and costs to individual i strictly depend on what individual i chooses. With joint adaptation, the benefits to individual i depend not only on what individual i chooses but also on what many other individuals choose as well. The fact that the benefits of individual actions are shared by others is the defining characteristic of joint adaptation. This interpersonal complexity explains why joint adaptation is more difficult to manage efficiently. If everyone was a Kantian philosopher, inclined to consider the implications of his actions on others, there would be no problem. Each person would equate total marginal benefits against marginal costs, taking into account not only their private gains but also the impacts on everyone else as well:

$$\sum_{j=1}^{n} dB_j/da_i = MC_i\,. \tag{10}$$

The adaptation a_i^* which would result from (10) would be efficient as it would maximize (9). The individual, in this case, considers not only his own benefits but also the benefits accruing to everyone else: $\sum dB_j/da_i$ for all j not equal to i.

In contrast, if the individual only considered the effect of his expenditure on himself, then the individual would use a more limited definition of marginal benefits:

$$dB_i/da_i = MC_i\,. \tag{11}$$

This would result in a level of adaptation a^1. Since for most public adaptations, $\Sigma dB_j/da_i > 0$, then it follows that $k^* > k^1$. The selfish individual would spend too little on joint adaptation.

Although (9) provides a general formula for public adaptation, individual cases will entail different functional forms for benefits. For example, sea walls being built in response to rising seas might have the following benefit function:

$$\max \sum B(a^{\min}, T) - \sum C(a_i)\,, \tag{12}$$

where $a^{\min}$ is the lowest level of adaptation in the entire group. The effectiveness of the sea wall is determined by the minimum height of the sea wall along its entire length. Thus, if one individual chooses to spend half as much on the sea wall as everyone else, the sea wall will be half as effective. Acting selfishly, an individual would only take into account his own benefit from the higher sea wall against his own cost and follow (11). In practice, if one individual builds a low sea wall, everyone else has an incentive to build the same low wall since the protection is determined by the lowest point. Instead of following (10) and building to protect the entire community, the sea wall is built to the specification of the person who cares least about the sea wall and provides only a small degree of protection.

A less severe example of public adaptation would have benefits depend upon total adaptation efforts. This case, which might resemble many public health alternatives, would have the following form:

$$\max \sum B_i\left(\sum a_j, T\right) - \sum C(a_i)\,. \tag{13}$$

The socially efficient response is to take into account the entire group's benefit from each individual spending more on abatement. The selfish response is to look only at what you gain yourself, following (11) instead of (10). The market result in this example is not quite as severe as the sea wall case, since the outcome will at least depend upon average selfish interests, not the minimum selfish interest. It is still true, however, that public adaptation will be underprovided by a market.

Government intervention could solve the problem of joint adaptation by supplying protection levels based on an efficient allocation (10). The government, acting on behalf of society-at-large would choose the efficient level of adaptation that maximized the group's net benefits. Total benefits and costs would be considered in every decision. Thus, government decisions, in addition to being concerned about direct group benefits, could also take into account externalities. For example, if controlling mosquitoes provided a health benefit but also posed an ecological cost, the government could weigh the value of this ecological cost into its decision making. In principle, joint adaptation can be handled efficiently.

In practice, however, governments may have difficulty providing efficient levels of joint adaptation. (1) Groups must perceive a collective gain. (2) The collective body must agree on the level of action. (3) Beneficiaries are often more interested in maximizing their private gain rather than maximizing the value to society. These three forces push governments away from efficient outcomes.

With private adaptation, actors who recognize climate changes and act accordingly are rewarded for adapting quickly. The same collective rewards hold true for joint adaptation but the rewards are shared by everyone in the group. An individual who spends personal resources becoming informed about her collective choices will receive the same reward as the individual who looks after only his own private affairs. Individuals do not have the same incentives to become informed and react quickly to collective problems. It is consequently more difficult to get a group to grasp collective issues than it is to get individuals motivated to look after their own private interests.

Conflict is inevitable in collective action. The benefits and even the costs of engaging in a collective action are rarely the same for everyone. Some of the alternatives will benefit certain members of the group more than others. Individuals will naturally press for the choice that maximizes their personal benefits. These choices need not be the same ones that maximize group net benefits. It is consequently difficult for groups to make efficient collective choices. In the sea wall example, the group must choose how high it should build the sea wall and when it should start. The most vulnerable homes along the sea might argue for a high wall to be built immediately. Owners of interior properties on higher land may be able to become beachfront owners if no sea wall is built. They may press for no action at all. The most efficient response could be anywhere between these two extremes. Encouraging political processes to pick the most efficient alternatives, however, is challenging and may be impossible (see Arrow, 1963).

Political processes do not appear to give efficiency great weight. Efficient collective action implies the activity maximizes the net benefits of the group. This definition of collective benefit, of course, pays no regard to who will benefit or pay for the action. Most individuals, however, are not indifferent to how these costs and benefits are distributed. Given that the beneficiaries rarely are the same people bearing the costs of collective actions, individuals will often lobby for activities that improve their personal fortunes regardless of the effect on the group as a whole. This is especially problematic when the benefits of an action are concentrated in the hands of a few whereas the costs are dispersed across many. Individuals from the public-at-large may not care which government action is undertaken as long as the costs per person are low. But powerful groups with concentrated benefits can reward themselves handsomely by swaying programs to meet their needs. Even without concentrated benefits, there is an incentive for potential beneficiaries to advocate too much government action, expecting the adaptation costs to fall upon the public-at-large. For example, individuals who choose to build their homes along the coast might be very enthusiastic about government programs to build sea walls expecting that the government as a whole will build the wall without assessing the beneficiaries the costs.

4. Dynamic Adaptation

Although one can model some adaptations adequately with a static analysis, adaptations that involve large capital stocks have important dynamic features. Climate change is a dynamic phenomenon, stretching over several decades if not centuries. Further, many sectors can only respond slowly to desired change and so the process of adaptation is itself dynamic.

Climate change is predicted to be a gradual process. This is not to say that there are no stochastic elements. Changes in temperature and precipitation are likely to continue to exhibit random fluctuations. Responses by ecosystems to these fluctuations could take on sudden dramatic proportions if they set off droughts, insect attacks, floods, or extensive fires. Nonetheless, the basic physical forces driving temperatures to rise will mount slowly and inevitably as greenhouse gases increase (Houghton et al., 1996). The best forecast of what will happen suggests a dynamic process of gradually rising global temperatures and precipitation levels (Houghton et al., 1996).

Because the process of change will take many decades to unfold, the timing of the adaptations need to match the climate changes. Quick adjusting sectors such as agriculture can adapt to climate as it unfolds. However, more capital intensive sectors may need to forecast climate change. That is, they may need to plan changes in anticipation of future climate change. Capital intensive sectors such as the coastal sector and timber require dynamic analyses of adaptation. They are also more reliant on ex-ante decisions since choices such as planting a tree or building a house have long-run implications and cannot be reversed easily.

A recent study of coastal property examined when and where to build sea walls along the coast of the United States (Yohe et al., 1996). By carefully building the sea walls only where needed and only when they were needed, the Yohe et al. study was able to reduce the present value of these adaptations by over an order of magnitude. For example, suppose a low sea wall ($500,000) would protect an important set of properties from being inundated in 2030 and a high sea wall ($2,000,000) would protect more properties from flooding by 2080. The initial studies of sea level rise ignored the timing of adaptation and simply chose the response with the smallest cumulative costs. These studies predicted society should choose to build the high sea wall at a cost of $2,000,000. The dynamic response calls for building the low sea wall just before 2030 and the high sea wall just before 2080. At a 5% real interest rate, the present value of the dynamic response is just $148,000, an order of magnitude less than the initial reported cost of $2,000,000.

Capital intensive sectors are vulnerable to rapid change. Sectors with substantial long-lived capital may not be able to adjust this stock rapidly. These sectors may find themselves depreciating capital more rapidly than normal in order to change their capital stocks to fit new conditions. In the example above, coastal buildings could be depreciated before they are flooded. Timber companies might want to harvest trees prematurely if the trees are not suited for warmer climates. Biodiversity managers may want to move habitats of endangered species to keep them in desired conditions. When large capital stocks need to be adjusted, it is expensive to change them quickly: managers may need to find less expensive dynamic solutions.

Of course, not all sectors are burdened with long-lived capital. For example, most of the farm equipment on modern farms have a relatively short life expectancy. Tractors and combines have only a short economic life span (5 to 10 years). A typical farmer would have between 10 and 20 chances to change his equipment in order to adjust to a climate change that takes a century to evolve. It is reasonable to expect that farmers will have ample opportunity to replace their machines to grow different crops or use different practices. Farmers would generally not have to prematurely depreciate their capital to adjust to climate change.

Sectors with more long-lived capital do not have this luxury. Coastal properties lying in the path of advancing seas may have only a decade or two before being inundated. They could attempt private protection by raising their property or building a private sea wall, but these options are often expensive and often only delay inundation. Eventually, many properties might have to be abandoned. Owners should depreciate the standing capital on these properties in anticipation of this event. For example, if the inundation is expected in 20 years, they should avoid any long-term improvements that require 20 or more years for payback. As the inundation becomes more imminent, they should reduce maintenance of the building. All these attempts to depreciate the building prematurely will help reduce the damages that inundation will eventually cause.

Forest owners may also want to engage in dynamic adaptation (see Sohngen and Mendelsohn, 1998) for two reasons. First, forest owners can plant a new species after harvest that is better suited for a warmer climate. For example, if they want to switch from a hardwood forest to southern pines, they could accomplish this task by planting the pines after each hardwood harvest. Second, owners could harvest existing trees prematurely if the trees were no longer in optimal conditions or were vulnerable to premature mortality from warming. Even with these changes, the adaptation is gradual. By assisting natural forces to move towards new equilibriums, dynamic market adaptation can make the needed transitions occur more quickly. Further, many of the damages from the transition such as premature death and poor regeneration can be mitigated. In the case of timber, where several of the ecological models predict enhanced long-term growth (VEMAP, 1995), dynamic adaptation could bring desired species into place more rapidly leading to enhanced economic benefits (Sohngen and Mendelsohn, 1998).

If adaptation must be dynamic, how important is ex-ante adaptation? In a recent paper on adaptation, Fankhauser et al. (1999) argue that it is important to distinguish between reactive and anticipatory adaptation, as though there will be many examples of both. However, in examining a large array of possible adaptations (such as Table I), it seems that most adaptation is likely to be reactive. That is, in most cases, it is sufficient that firms, individuals, and governments react to the climate as it is observed to change. There is little additional benefit to acting in anticipation of a predicted change in climate.

With long-lived assets, there is a case to be made for anticipating how climate will change over the life of the asset. For example, a new forest, a new building along unprotected coasts, and a dam all could be affected by climate change over the lifetimes of such investments. If one had a prediction of how climate was likely to change over time, it would be prudent to include that prediction in designing the investment. In practice, however, there is a great deal of uncertainty surrounding what will happen at a specific location. Although we may have some confidence that global temperature and precipitation will increase, it is difficult to predict what is going to happen at a local level. Global precipitation might rise by 7% but a local watershed might experience a 20% increase or decrease in runoff. Global temperatures might rise by 2 °C in 2100, but local temperatures might rise by more or less. Uncertain local climate predictions make it difficult to know how to adapt in advance. Uncertain ecological responses to changing climate further complicate the picture. Species shifts in a watershed, for example, could alter runoff by changing evapotranspiration. Climate change is expected to occur slowly so that large changes in climate and ecosystems may not occur for three or more decades. The present value of such changes tends to be low, encouraging dams and similar facilities to be built for current conditions. An analysis of water supply projects suggests that climate change is not likely to have much effect on the present value of most projects (Bennett and Mendelsohn, 1997).

One circumstance where anticipatory adaptation might be important is when there are known climate thresholds. If one were approaching a threshold where a negative impact would suddenly appear, it is possible that one would want to anticipate this event prior to observing it. This would require predicting changes in temperature and precipitation and possibly ecosystem responses as well. Armed with this advanced warning, managers could engage in preventive measures before the incident takes place. For example, one could predict when enough warming has occurred that there could be widespread fires in natural ecosystems. Rather than waiting for a fire to sweep across large landscapes in a single devastating event, managers could engage in some advanced harvests and isolate forests from each other. Fires would still take place and the ecosystem would still adjust, but the change need not be a catastrophic event.

One of the most important thresholds in natural systems is species extinction. Climate change may threaten already endangered species and lead to their extinction. To reduce the chances of extinction, private and public land owners can take preventive actions to move threatened species to more secure habitats before they are lost. Rather than simply focusing on building walls around existing habitats, conservation strategies might have to actively seek changing where such species lived. By carefully planning a path of change, managers could assure that the threatened species survived the transition.

5. Conclusion

This paper discusses the importance of efficient adaptation. The analysis distinguishes between private and joint adaptation. Firms and people will adapt to serious environmental changes such as climate change by engaging in many forms of private adaptation. These alterations of behavior will mitigate some of the potential harms from climate change, especially in key market sectors. As a result of private adaptation, the magnitude of harm will be reduced and the size of benefits will increase, in farming, forestry, recreation, and energy. Since private adaptation is done for private gain, there is no public policy required for the adaptation to take place. These privately rewarded adjustments will proceed on their own.

Of course, it is reasonable to question whether this optimistic forecast is realistic. One intriguing avenue of research should establish some experiments where individual farmers or other actors are tracked over time to see how quickly they do adapt to future changes in climate. If people do react with delay, it will be important to model these inefficiencies in future climate change models.

In contrast, joint adaptation will likely depend upon government action, since the shared benefits associated with joint adaptation results in underprovision by markets. Joint adaptation will be especially important with respect to water supply, coastal protection, health protection, and ecosystem preservation effects. However, even with government intervention, it is not clear whether joint adaptation will be efficient. People will disagree about how much adaptation is desirable, they will argue about who should pay for it, and they may try to manipulate the process for private gain. It is consequently more difficult to predict how much joint adaptation will take place and how efficient it will be.

Policy makers must be especially cognizant that joint adaptation frequently must be dynamic. The efficient response to climate change will often be a series of subtle changes over time. The problem often cannot be solved with a single one-time action. Policy makers need to be able to think in long time horizons and pursue solutions as they are needed. A dynamic policy is especially important in capital intensive sectors such as ecosystems, coastal protection, and water supplies. As nature changes, policies need to change accordingly. Through a judicious use of dynamic policies, adaptation costs and remaining impacts can be reduced substantially. The challenge for policy makers is to create incentives for public institutions to make joint adaptation as efficient as possible.

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