The Economics of Adaptation to Climate Change in Developing Countries

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Abstract

Adaptations are changes in behavior and capital motivated by climate change. Economic theory suggests that adaptations are efficient (desirable) only if their benefit exceeds their cost. Private adaptations are likely to be efficient because the benefits and cost accrue to the decision maker. With some important exceptions, private adaptation is likely to be done efficiently by markets. Public adaptations, however, benefit many people. Markets are not likely to make efficient public adaptations because they cannot coordinate payments from multiple consumers. Governments need to be responsible for public adaptations. However, government must think carefully about being efficient. Empirically, little is known about what precise changes in behavior are efficient, where such changes should take place, and when they should take place. The empirical literature has largely focused on how actors have adapted to the current range of climates across the earth. From these studies, researchers are extrapolating what changes would make sense in the future as climate changes. The results suggest that adaptations are local in nature and therefore look like patchwork adjustments across space. They depend on the current local climate, how it changes, and many local conditions. Although public adaptations in health and conservation look promising, there are virtually no economic analyses of their potential. Overall, adaptation can be very effective at reducing damages and seizing opportunities. Research must now focus on making the practical steps that turn that potential into reality.

Introduction

How much climate change will occur in the future will depend on the extent of mitigation that the global society finally agrees to do (IPCC 2007a). However, given the high cost of mitigation and the difficulty of making aggressive changes in our emission path, societies will very likely face some additional climate change in the years to come. Every society must therefore confront what they should do to adapt to climate change. Adaptation is any change in behavior that an actor (household, firm, or government) makes to reduce the harm or increase the gains from climate change. With changing global climates across the world, virtually everyone should change their behavior. The difficult questions are: which behaviors need to be changed, where should they change, and when should the change take place? This paper discusses the answers to these difficult questions for a specific region of the world- developing countries.

Efficient adaptations are the set of adaptations that maximize net benefits. That is, the benefit of an efficient adaptation is greater than the cost. Not every adaptation is efficient. For example, building a sea wall that costs $5 billion to protect land that is worth $1 billion is not efficient. The only adaptations that are desirable are efficient ones. If the cost of a change exceeds the benefit, the adaptation actually makes society worse off. Such adaptations should not be encouraged. Whether any specific change is efficient will depend on where it is done and when it is done. Getting both the local conditions right and the timing right is critical.

Low latitude countries are predicted to bear over three fourths of global climate damages (Mendelsohn et al. 2003). The low latitude countries are both developing and emerging countries. Because they are near the equator, they already face warm climates. The hill-shaped nature of most temperature damage functions predicts that warmer temperatures will be especially harmful for people and firms in warmer climates (Mendelsohn and Schlesinger 1999).

Developing countries are particularly vulnerable to warming. They tend to have a disproportionate share of their GDP in climate sensitive sectors (especially agriculture). They will consequently have higher impacts as a fraction of their GDP. They are also more vulnerable because they tend to have weak governments. It is not clear that many of the governments of developing countries are capable of mounting effective public programs to counteract climate impacts. The governments of developing countries may be particularly ineffective at adapting to climate change. Many developing countries also have weak markets. The absence of property rights will discourage many private actors (firms and households) in developing countries from adapting efficiently as well.

The concentration of climate change damages in developing countries raises serious equity issues. Most of the world’s poor live in developing countries. The fact that these people will bear the brunt of climate damages is a particularly troublesome aspect of climate change. This is exacerbated by the observation that developing countries have low greenhouse gas emissions.

Developing countries are responsible for only 7% of global emissions, versus emission from developed (45%) and emerging (48%) countries. The 2.3 billion people in developing countries are consequently bearing a disproportionate share of the damages caused by the emission behavior of other people in developed (1.2 billion) and emerging (3.0 billion) countries. One can therefore argue that there are equity perspectives that make efficient adaptation in developing countries a global issue.

This paper begins with a formal discussion of the economic theory of adaptation in the next section. We then move to a discussion of the empirical adaptation literature with a focus on developing countries. The paper concludes with a discussion of what remains unknown about adaptation and what research is most sorely needed.

Theory of Efficient Adaptation

In order to understand how households will respond to climate, one must first understand how climate directly affects household decisions. Let us begin with a model of the direct effects of climate on households. We imagine a utility function (U) that entails goods (X) but also contains climate (C). The individual maximizes utility subject to a budget constraint determined by income (Y):

$$\text{Max } U(X,C) \text{ s.t. } Y=PX$$

where P is a vector of prices. Using Roy's Identity, we can identify a set of demand functions for this individual:

$$X_1=D_1(P,Y,C)$$

$$X_2=D_2(P,Y)$$

For a vector of goods, X_2, C will not play any role. That is, households will purchase these goods at the same amount no matter what the climate is. However, for another vector of goods, X_1, C will shift the demand function. For example, the number of ski trips may go down as temperature increases but the number of summer recreation trips will go up. The desire to buy a convertible as a feature of a car may go up with warmer temperatures but fall with higher precipitation. Consumers will presumably make the changes that make them better off. Given the price of skiing, they will decide how many fewer days to go in a warmer winter. This change in behavior due to climate is adaptation. If it makes the household better off, it is an efficient adaptation. Presumably, households will engage in efficient adaptations precisely because the changes increase the utility of the household. Of course, if households do not know that a new behavior will make them better off, they may not engage in it. However, all that it would take to encourage efficient adaptation is information.

Some of the decisions by households involve buying capital goods. To model capital goods, it is necessary to discuss the role of time. In the case of a capital good, the household is trying to maximize utility over time. The household must weigh the stream of annual utility they perceive that they get from the asset against the cost of the asset.

$$\text{Max} \int U(X,C,K)\, e^{-rt}\, dt \quad \text{s.t.} \int [Y_t - P_x X_t] e^{-rt} dt - P_k K$$

where the asset is bought at the start of the analysis. If the marginal utility from the asset varies with climate, climate change will affect how much capital the household buys. If their choice of asset changes, it is an adaptation. For example, given the price of buying a convertible car, the household will decide whether to switch into a convertible. If higher temperatures increase the benefits that they receive from a convertible, they will more likely buy a convertible. However, the higher temperatures must occur during the lifetime of the car or they will not get accrue these higher benefits. People will therefore likely wait until the higher temperatures are imminent. It is also true that they will be highly conscious of the value of their existing car and will not sell it prematurely unless there is a good used car price for the remaining years of the car. That is, people will be careful about prematurely scrapping their existing car to take advantage of instant warmer temperatures. They will more likely wait until their existing car is near its terminal age before changing. Adaptations involving capital are likely to be much slower than adaptations involving daily consumer purchases. The more rapidly that climate changes, the more difficult it is for households to fully adapt their capital.

Modeling firm decisions is very similar except that firms maximize their profits (π) rather than a utility function:

$$\text{Max } \pi = P_Q Q(Z,C) - \Sigma P_Z Z$$

Where P_Q represents the prices of output Q, P_Z represents the prices of purchased inputs Z, and Q(Z,C) is a production function. With firms, climate enters the production function and alters the relationship between inputs and outputs. The role of climate in production functions can be nonlinear. For example, in agriculture and forestry, temperature and precipitation tend to have hill-shaped relationships where productivity at first increases and then decreases with warmer temperatures. However, with coastal structures, the relationship is more monotonic with increases in sea level strictly increasing costs. As climate changes, firms will experience either productivity increases or decreases. This will cause them to change their inputs because the marginal productivity of inputs will often change. In certain circumstances, it may cause them to shift their outputs as well. For example, if warming makes one output much less profitable, they may decide to shift to a new output that is now more profitable than before. For example, farmers may shift which crop to grow or which animal to breed with climate change.

As with households, firms also invest in capital (K). Again, one must examine these investments with an intertemporal model. In this case, firms are maximizing the present value of future profits. Assuming that the investment in capital happens in the first period, the profit maximization decision is:

$$\text{Max} \int [P_Q Q_t(Z,K,C) - \Sigma P_Z Z_t]\, e^{-rt} dt - P_k K$$

where P_k is the price of capital. Looking at the first order condition of this decision, the firm will equate the price of capital with the stream of marginal productivity gains from the last unit of capital over time:

$$P_k = \int P_Q \partial Q_t(Z,K,C)/\partial K\, e^{-rt} dt$$

If climate increases (decreases) the marginal productivity of capital, the firm will invest in more (less) capital. The firm, however, will be reluctant to prematurely abandon existing capital and so it will wait for existing capital to depreciate before acting. As with households, firms will be slow to adapt capital as climate changes. The more rapidly climate changes, the more difficulty firms will have adjusting their capital stocks. More rapid climate change therefore involves higher costs with capital intensive sectors such as the coastal (sea level rise) and forestry sectors.

With both firms and households, the decision to adapt involves only their own welfare. We define such adaptations as private. The costs and benefits of private adaptation accrue to the decision maker. Because the decision maker is interested in maximizing welfare, the only adaptations they will consider are efficient. Private adaptations are likely to proceed without any public policy incentives or government involvement.

Poor individuals and small firms may make different decision than wealthy individuals and large firms. Poor individuals are constrained by their income to inexpensive adaptations. Wealthy individuals can consider more alternatives because they have more money to spend. However, it is not necessarily true that wealthy families will find it easier to adapt than poor families. The outcome for each household will depend on the extent that climate affects them and what alternatives are available. So a poor family that is barely affected by climate will not have much adaptation to do. Similarly, a poor family may have many alternatives to adjust to climate change compared to a wealthy family. For example, wealthy families that have specialized in goods and services that are tied to a temperate climate may be more vulnerable than a poor family that depends on goods and services based on a tropical climate. Governments and NGO's may feel compelled to help poor families adapt because of concerns about equity, but if poverty is the only constraint facing a poor household, the only reason to help is equity. This can be more difficult than it seems because the third party must understand the local conditions and desires of the targeted audience. Third parties must be careful to design programs that are truly helpful to their targeted audience or they may well be wasting their efforts. The measure of success is not the amount of money spent but the improvement in welfare of the targeted population.

In discussing firms and households, we have so far taken a very micro approach as if climate affects only one household or firm. In practice, climate change is going to affect the whole world. It may not have the same effect everywhere and in some cases effects in one place can offset effects elsewhere. However, there are certainly going to be many circumstances where climate affects the aggregate demand and or aggregate supply of specific goods. If households increase (decrease) their demand for a specific good, the demand function will shift outwards (inwards). The good will become more (less) scarce and prices will respond accordingly. This will cause suppliers to react. With more scarce (plentiful) goods, prices will increase (decrease), and suppliers will try to make more (less) of the good in response. The market reactions will lead to indirect effects of climate on suppliers. Their change in production is a market adaptation. Similarly, if aggregate production falls (increases), goods will become more (less) scarce and consumer s will react by buying less (more) of the good. In this case, consumers will be affected indirectly through the market leading to a change in the goods being bought and sold in that market. Markets lead to important indirect adaptations for goods that are traded. When markets change because of adaptation, the impacts of climate change are felt throughout the world, not just in the places where the direct impacts first occurred.

The adaptation literature has made a careful distinction between adaptations that are made in advance of climate change (anticipatory) versus adaptations that are made after the climate changes (reactive). In a perfect information world, adaptations would be timed to occur precisely as the climate changes. Of course, changes that involve a great deal of planning would have to be considered before the climate changes. But the change itself could wait until the climate actually alters. An important exception to this rule is changes that should be done anyway (no regret strategies). Of course, there is no reason to wait for climate change if there is every reason to make a change under current circumstances.

If climate change is uncertain, however, it is difficult to do anticipatory adaptation. Because adaptations are largely local, the climate that matters is the future local climate. This is highly uncertain because climate models are not yet very good at predicting what is going to happen in each place (especially precipitation changes). Under uncertainty, it is likely to be a lot more effective to engage in reactive adaptation than anticipatory adaptation. Once it is clear how local climate has changed, this uncertainty is resolved. It is likely that the bulk of adaptation will be reactive. Of course, actors should do contingent planning in advance. They should think about how they would react if climate changes one way or another. They should invest in research to understand what future choices would be most effective in different circumstances. This will allow them to be more responsive once it is clear how climate has changed.

One special concern with developing countries is that many firms and households lack secure markets. For example, they may lack private property rights. Many farmers till land, graze animals, and harvest trees on common property. Although there are some rare examples of efficient community organization of common property, they tend to involve very low levels of investment into the land. With modern agriculture, livestock, and forestry methods, common property tends to lead to underinvestment in the natural capital. Each household obtains a large private reward from harvesting the natural capital and yet must share in the benefits of any investment into that capital. There is limited incentive for private actors to make any capital investments to adapt to climate change. Similarly, firms that are concerned about the security of private resources, will under invest in a places where property rights are risky and so will not completely adapt to climate change. Finally, households and firms that have no access to the capital market will not be able to borrow to make capital investments to adjust to climate. These market imperfections may well lead to firms and households in developing countries failing to efficiently adapt to climate change. Efforts to help the affected households, however, should be directed at eliminating the root cause of the problem rather than directly paying for adaptation. Providing access to capital markets and secure property rights is a sufficient response. Because it is difficult to determine what each household should do to adapt to climate change, it is very difficult to develop third party programs that direct private adaptation efforts.

Although firms and household s are likely to engage in efficient private adaptation, there are reasons to expect that these actors will not be very good at doing pubic adaptations. Public adaptations are changes that will benefit many actors. The efficient choice is to maximize the net aggregate benefits:

$$\text{Max } \Sigma b(Q)-C(Q)$$

where b(Q) is the benefit to each household from adaptation Q and C(Q) is the cost of the program. Note that this is very similar to private adaptation except that there are many beneficiaries.

As with all public goods, markets can handle public adaptations only if they can effectively collect revenues from multiple consumers (Samuelson 1954). There are some special cases where consumers have similar demand functions, where markets can effectively deliver public goods (for example, movies or clubs). However, when consumers are heterogeneous, it is difficult to coordinate collective payments and public goods are underprovided. Examples of typical public adaptations are seawalls that would protect everyone behind them, dynamic conservation that might protect species or ecosystems for the benefit of the many people who enjoy them, and mosquito control that might reduce illnesses to a local population. Public goods are the "economic" argument for governments. Governments can coordinate across heterogeneous citizens to create an "aggregate demand" for a service. Governments are needed to encourage public adaptations.

In theory, the very incentives that make private actors want to engage in only efficient adaptation applies to local government as well. By backing all projects whose benefit exceeds the cost, the government is working effectively for their citizens. However, with public goods, there is not a perfect match between who pays for a good and who benefits. It is therefore possible for citizens who get more of the benefit to want to have too much of the service provided and for citizens who pay too much of the cost to want too little. There is no guarantee or even a good track record that governments will be efficient. Therefore there is no particular reason to believe that governments will suddenly be efficient with respect to public adaptations. This is one of the reasons why it is critical that more research be done on public adaptations. Governments need advice concerning how they should proceed.

Again there is a reason to be concerned about public adaptation in developing countries. Many developing countries have weak governments that do not serve the citizens at large. Weak governments are not likely to be effective at public adaptations either. They are likely to do too much adaptation to benefit a few chosen citizens and not enough adaptation to benefit everyone else. There may be a strong need for international governmental organizations to assist developing countries to provide public adaptations.

For developing countries, another effective adaptation strategy is development itself (Schelling 1992). One of the reasons developing countries are particularly vulnerable is that they have a large share of their economy in climate sensitive sectors, namely agriculture. Development can encourage a more robust economy by developing service, manufacturing, and other sectors of the economy. Development could even be helpful to the provision of nonmarket services as it would provide resources for the country to pursue all of its goals. Of course, for development to be effective, it must be targeted to improving the economy of the developing country. Development which is largely just income transfers (welfare) would not necessarily achieve this purpose.

Another side benefit of development as an adaptation strategy is that it can be an effective compensation scheme. Development can lift people out of poverty in the long run. Of course, helping countries develop would likely increase their energy demand which would make mitigation more difficult. But mitigation policies that are based on keeping the world's poorest people in poverty could well be just as harmful as climate change itself.

Empirical Adaptation

In contrast to the theory of adaptation which is well developed, the empirical adaptation literature is in its infancy. The ideal empirical experiment is to observe how randomized actors respond to different levels of climate change over time controlling for all other intertemporal changes. Unfortunately, there has been so little climate change to date, that the intertemporal record is dominated by non-climate factors such as economic development, price changes, and even technological change. For example, the climate has changed approximately 0.5°C over the last fifty years. This is about 10% of the difference between high and low daily temperatures and about 2% of the difference between winter and summer temperature. From 1950 through 2000, GWP has increased 1000%, world population has increased 240% and agricultural productivity per hectare has increased 270%. It is very difficult to see the impact of such a subtle shift in climate against the backdrop of such dramatic changes in other factors. The intertemporal record may be more convincing in the future as climate change progresses, but it is not a good source of information yet.

An alternative place to look for empirical evidence is to look at how people, firms, and governments have adapted to the range of climates that exist locally today. People live in climates that range from the Arctic to the Equator. Average annual temperatures range from -20°C to +30°C across this range of the planet. The cross sectional variation in temperature provides a powerful signal to test for climate adaptations. Of course, one cannot observe all sectors from the Arctic to the Equator, but even if one stayed within narrower continental ranges, there is still substantial temperature variation across space.

For each climate sensitive sector, there are a number of adaptations that actors can do that are climate sensitive. To determine whether a behavior is climate sensitive, one merely has to test whether behavior changes across different climate zones. In order to quantify the climate sensitivity of choices, the choice can be regressed on climate and other control variables. If the climate coefficients are significant, the choice is one of the adaptations that an actor can make to adjust to local climate. As climate changes, the choice should change as well. Assuming the actor efficiently adapts to her current local climate, the regression provides insight into what she must do to adapt to a new climate. For most decisions, responses are not the same everywhere because they depend not only on climate but a myriad of local conditions.

Agriculture

In agriculture, the amount of land that is farmed is sensitive to climate. Controlling for other factors, Mendelsohn, Nordhaus, and Shaw (1996) find that US farmers are more likely to farm a hectare of land in moderate temperatures. With moderate warming, the increase in farmland in the northern United States offsets the decrease in farmland in the southern United States. However, as warming exceeds 3°C, the losses in farmland begin to outweigh the gains and the US loses aggregate farmland. This implies that in climates warmer (cooler) than the United States, the amount of farmland may drop (increase) immediately as climate warms.

The choice of crops is very climate sensitive. Farmers in Africa are more likely to plant fruits and vegetables and millet and less likely to plant maize and groundnut as temperatures warm (Kurukulasuriya and Mendelsohn 2008). Farmers in South America are also more likely to plant fruits and vegetables but less likely to plant wheat and potatoes as temperatures warm. Whether they plant more or less squash, rice, or soybeans depends upon where they are in South America (Seo and Mendelsohn 2008b). Farmers in China are more likely to plant cotton and maize and less likely to plant soybeans and vegetables as temperatures warm (Wang et al. 2010). The responses differ across continents because they grow different crops and have different ranges of climate.

The choice of livestock is also climate sensitive. African farmers are more likely to raise sheep and goats as temperatures rise and less likely to raise dairy and beef cattle (Seo and Mendelsohn 2008c). Whether they increase or decrease their reliance on chickens depends on their current climate. South American farmers are more likely to raise sheep and less likely to raise beef and dairy cattle (Seo, McCarl, and Mendelsohn 2010). Their choice of pigs depends upon their current climate.

In general, the marginal productivity of inputs (fertilizer, machinery, expensive seeds, etc.) is higher on more productive land. Since climate plays a role in determining productivity, it will affect these decisions. For example, the choice of irrigation depends heavily on precipitation in Africa (Kurukulasuriya and Mendelsohn 2007). Although irrigation also makes crops less vulnerable to higher temperature, farmers are more likely to adopt irrigation in cooler places. Higher temperatures increase the amount of water needed, increasing costs.

Water

The discussion of irrigation in the agriculture sector reveals that the water and agriculture sector are closely linked. A large fraction of consumed water goes to agriculture. However, irrigation demand is very price sensitive. The marginal productivity of water is low so that farmers cannot afford to pay a lot for more water. In contrast, urban and industrial uses of water have very high values. If the fraction of water used by each water user remains fixed and climate change causes a drop in runoff, there would be very high damages from losses of water to urban and industrial users. By reallocating water form low valued uses to high valued uses, however, it is possible to dramatically reduce the damages from runoff reductions. Studies of the Colorado River predict damages can be reduced substantially by reducing low valued uses (upriver irrigation projects). Water for the major dams and the valuable downriver cities would be preserved (Hurd et al. 1999). Studies of other river systems produce similar results suggesting that moving water from low to high valued uses will be an effective adaptation if runoff falls (Hurd et al. 1999; Hurd et al. 2001). A similar result occurs in California where a complex model of the canals and rivers of California suggest large shifts in water use if runoff falls (Lund et al. 2006). As the lowest valued user of water, agriculture is clearly affected by this reallocation. However, even within agriculture, water can be reallocated from low valued to high valued crops. By reducing low valued agriculture in the Central Valley, the state could absorb a 25% reduction in runoff with only a 3% reduction in agricultural GDP and virtually no losses for urban and industrial uses (Howitt and Pienaar 2006). Farmers can also adjust by adopting water saving technology such as sprinklers and then drip irrigation (Mendelsohn and Dinar 2003; Dinar et al. 2011).

Coastal

Another sector where adaptation is very important is the coastal sector where sea level rise threatens to inundate valuable coastline. If there is no reaction, gradually rising seas will cause coastlines to shrink inland. The land and structures along the coast will be lost. Although this would cause very high damages if it occurred suddenly, it is predicted to unfold gradually over centuries. There are two adaptations that society can make. By anticipating inundation, structures along the coast can be depreciated. Buildings that are slated for near term destruction can be allowed to deteriorate, thereby reducing the value of the capital lost (Yohe et al.1999). However, an even more effective strategy is to build hard structures to defend the coastline. If the government can organize effective sea walls to be constructed along entire stretches of coast, the area behind the walls can be protected. The value of most developed land is sufficiently high that it would pay to build moderately high sea walls over the next century to protect all developed coastlines from inundation (Yohe et al. 1999; Neuman and Livesay 2001, Ng and Mendelsohn 2005). Undeveloped land (mangroves, marshes, and beaches) should be allowed to migrate inland. This would happen naturally provided that there are no barriers inland. Especially valuable natural lands could be preserved in place with underwater sea walls (Ng and Mendelsohn (2006). For example, the most valuable beach in Singapore could be protected by building sea walls offshore that would allow the beach to be raised. Care would have to be taken not to create danger zones too close to the beach. Such an adaptation, however, would be very expensive and so would be reserved only for very high valued uses that would otherwise be lost.

Forestry

Adaptation can also play a role in forestry (Sohngen and Mendelsohn 1998; Sohngen et al. 2002). Changing climate is expected to alter the location of ecosystems and therefore change whether particular species of trees can be grown in a local area (IPCC 2007b). Forestry can assist dynamic ecological processes by planting new trees in anticipation of expanding locations and harvesting trees in places where the existing trees are expected to die back. Changing the intensity of forestry is another way that the forest sector can adapt to change. If there are anticipated shortages (abundance) of future timber caused by climate change, the industry can plant more (less) plantations to mitigate the shortfall (abundance). Another boundary the forest sector can change is the edge between managed forests and "economic wilderness" (unused forests). With shortages (abundance), the sector can expand (contract) managed forests.

Energy

Changing climate will potentially affect interior temperatures making life potentially far more uncomfortable. However, it is likely that people and firms will react and cool more in summer and warm less in winter. In a temperate climate, the total BTU's used would roughly offset (Rosenthal et al 1995). However, cooling is more expensive than warming, so although the total BTU's might not change, the costs of staying comfortable will increase (Morrison and Mendelsohn 1998). Although the added cooling cost is often treated as a damage from warming, it is really the cost of the adaptation. For developing countries which have relatively small winter heating costs, the net potential damages from higher cooling costs could become large as they become wealthier (DePaula and Mendelsohn 2010). In addition to shifting towards cooling, people will also change fuels (Mansur et al. 2008). Warming will cause an increase in electricity demand and a reduction in other heating sources (primarily oil and natural gas). With the desire for more cooling, there will also be an increase in cooling equipment. Households will move from fans to portable air-conditioners to central air conditioning. This increase in capital will in turn lead to more cooling.

Health

Climate is expected to make three changes that could affect human health: vector borne diseases, heat stress, and ozone formation. All of these threats to human health already exist. Climate change will simply exacerbate the problem. Vector borne diseases change because the animals that carry the disease can move into new territories. For example, warming and precipitation increases can expand the territory of harmful mosquitoes or biting flies. As these territories expand, additional human populations can be infected with the disease. Abnormal increases in temperature are known to cause heat stress which raises acute mortality rates. People in relatively cool climates seem particularly vulnerable. Finally, warmer temperatures increase the rate at which nitrogen oxides and volatile organic compounds form into ozone, increasing human exposure to ozone.

There are currently many effective strategies to deal with each public health problem. Vector borne diseases can be controlled with public health measures (Ebi 2008). For example, vectors that carry disease can be controlled as with tick or mosquito spraying. People can take preventive measures to avoid exposure by using mosquito netting or wearing insect repellants. Finally, the disease can be treated once it is contracted with antibiotics and other medical responses. Heat stress deaths can be limited by warning systems, limiting strenuous behavior during a heat wave, and providing threatened individuals with protective shelter that is adequately cooled (Ebi et al. 2004). Higher ozone concentrations can be prevented by controlling the precursors to ozone: nitrogen oxides and or volatile organic compounds. Unfortunately, there are few economic analyses of the costs and benefits of these alternative responses to the threat of climate change. A great deal of the literature has simply predicted potential deaths assuming no adaptation whatsoever.

Conservation

Quantitative ecological models are quite clear that climate change will alter ecosystems worldwide. In addition to changes in Net Primary Productivity (NPP), there will also be wholesale movements of ecosystems poleward and to higher altitudes. As ecosystems shift, the ecosystem services that they provide will change. Habitat for most species will shift as well. This implies massive global changes in ecosystems. Efforts to preserve specific ecosystems in place (within narrow geographic confines) will be challenged by these dynamic forces. Endangered species which depend on very local conditions will be threatened. Potentially many species could be lost and many parks and recreation areas could be vastly altered.

Quantitative ecologists have begun to move from modeling equilibrium ecosystem outcomes to studying ecosystem dynamics. These studies have examined how ecosystems have changed in the past in reaction to large global forces such as the glaciers advancing and retreating, catastrophic fires, and ubiquitous insect attacks. The dynamic analyses reveal that ecosystems generally are in flux, reacting to natural as well as manmade disturbances. Conservation efforts can be redirected towards managing these dynamic forces rather than setting aside parcels of land that hold particularly desirable (though temporary) outcomes. For example, land planners can design corridors for ecosystems to move across space rather than just protect isolated patches. Conservationists can actively manage for transitions by planting trees and plants that are suited for a slightly warmer climate. They can remove dead and dying species in places that can no longer support specific plants. They can design habitat for or eliminate predators of endangered or just highly valued species. They can use fire to help ecosystems move in desired directions rather than fighting fires across the board. Unfortunately, no economic analyses of these dynamic adaptations have yet been done.

Aggregate Adaptation

In addition to the microeconomic studies of adaptation by sector, there have also been some attempts to measure aggregate adaptation efforts. International agencies responsible for funding adaptation have estimated what funding they would require in the future. The annual estimates range from $28-67 billion (UNFCC 2007) to $75-100 billion (World Bank 2010). However, these estimates should not be taken too seriously because they tend to include very expensive and inefficient capital projects that would likely not pass cost benefit tests.

Some authors have also tried to use Integrated Assessment Models to talk about the tradeoff between mitigation and aggregate adaptation (De Bruin et al. 2009; Agrawala et al. 2010; Bossello et al. 2010). These models suggest that adaptation is likely to be very important to climate change and that adaptation and mitigation complement each other. The ideal strategy is to engage in both. The authors have also investigated whether it is better to plan future adaptation activities in advance or react to climate change as it unfolds. If planned research improves R&D sufficiently, it can lower future adaptation costs substantially. Of course, planning for adaptation and actually doing adaptation in advance of climate change are two different things. With the very high uncertainty about local climate change, it is very difficult to adapt before local climate changes are evident, especially changes in precipitation patterns.

Conclusion

There has been a great deal of theoretical work done that defines climate adaptation. The literature has made it clear that not all adaptations are desirable. Society wants to identify and implement only efficient adaptations whose benefits exceed their cost. The literature has identified important distinctions between private and public adaptation. Private actors will generally adopt efficient private adaptations without public policy interventions.. However there are important exceptions with common property, with poorly protected private property rights, and where there are market failures that private adaptation will likely be inefficient. These problems require institutional responses to create desirable private incentives. It is also critical to recognize that markets will under provide public adaptations. Governmental policies are needed to provide public adaptations efficiently. The problems requiring a policy response may be particularly acute in developing countries because they have so many market failures and because they have weaker governments.

The empirical research supporting adaptation is in a more developmental stage. Although there are good examples that identify some efficient adaptation responses in some sectors and some places, more research is badly needed. Adaptation in agriculture has been frequently studied, but even here all the choices that farmers should be do in each place and at each moment in time are not clear. Current research suggests that farmers should adjust how much land should be farmed, what farm types to use, what crops to grow, what animals to raise, and what inputs are needed. The pattern looks like it will vary a great deal over space and time. But more research is needed to pin down what makes sense in each contingency. Institutional changes such as encouraging private property to replace common property and public lands are important to farmers especially in developing countries. But it is not clear what land should be privatized and exactly how that process should be designed. Research and development into new crop varieties and breeds may give farmers important new choices but such advances may be difficult to achieve.

Other sectors should also adapt. Water should be reallocated from low to high valued uses. What additional capital investments should be made in the water sector are less clear. Should more or less dams be built? Will there be a greater or lower demand for new canals? What changes should be made in levees to protect against flooding? Coastal structures should be built to protect valuable developed coast lines. When they should be built and how high they should be needs to be determined. Forests need to be adapted to changing ecological conditions. What precise changes are needed in each forest needs to be perfected. Space heating and cooling will certainly change as climate changes. This is complicated in developing countries as income changes will also bring rapid adjustments in cooling. Many places have not yet been studied. Research on adaptation is sorely needed in most developing countries.

Perhaps the general area that needs the most attention in adaptation research, however, concerns nonmarket sectors. What should be the public health response to potential deaths caused by climate change? How many of these deaths can be avoided and at what cost? How should conservation change in light of a changing world? How should dynamic forces be managed to get the highest valued stream of services from ecosystems over time? What public adaptations are efficient in each place and time?

Overall, adaptation is going to involve a mixture of changing capital and changing behavior. It is unlikely that the world will change both perfectly efficiently over time. However, with careful analysis, we can hopefully encourage a great deal of efficient adaptation to take place to take advantage of new opportunities provided by climate change and to reduce potential damages that would otherwise occur.

References

Agrawala S., F. Bosello, C. Carraro, E. De Cian, E. Lanzi, K. De Bruin, R. Dellink (2010) "PLAN or REACT? Analysis of adaptation costs and benefits Using Integrated Assessment Models", OECD Environment Working Papers, No. 23, OECD Publishing. doi: 10.1787/5km975m3d5hb-en.

Bosello F., C. Carraro, E. De Cian (2010) "Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage", *Climate Change Economics*: **1**: 1-22.

De Bruin, K. C., R. Dellink and R. Tol (2009) "AD-DICE: An Implementation of Adaptation in the DICE Model," *Climatic Change*: **95**: 63–81.

Dinar, A. Fleischer, A. and R. Mendelsohn. 2011. "Bundling Agricultural Technologies to Adapt to Climate Change Technological Forecasting and Social Change" *Technological Forecasting and Social Change (forthcoming).*

Ebi K. (2008). Adaptation costs for climate change-related cases of diarrheal disease, malnutrition, and malaria in 2030. *Globalization and Health*: **4**: 1-9.

Ebi, K., Teisberg T.J., Kalkstein L.S., Robinson L. and Weiher R.F. (2004). Heat Watch/Warning Systems Save Lives: Estimated Costs and Benefits for Philadelphia 1995-1998, *Bulletin of the American Meteorological Society*, 85: 1067-1073.

Fankhauser, S., Smith, J., and Tol, R. 1999, "Weathering Climate Change: Some Simple Rules to Guide Adaptation Decisions" *Ecological Economics* **30**, 67–78.

Goklany, I. 1995, "Strategies to Enhance Adaptability: Technological Change, Sustainable Growth, and Free Trade" *Climatic Change* **30**, 427–449.

Howitt, R. and E. Pienaar. 2006. "Agricultural Impacts" in J. Smith and R. Mendelsohn (eds.) *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California.* Edward Elgar Publishing, Northampton, MA. pp 188-207.

Hurd, B., J. Callaway, J. Smith, and P. Kirshen. 1999. "Economics Effects of Climate Change on US Water Resources" in R. Mendelsohn and J. Smith (eds) *The Impact of Climate Change on the United States Economy*. Cambridge University Press, Cambridge, UK pp. 133-177.

Hurd, B. and M. Harrod. 2001. "Water Resources: Economic Analysis" in Mendelsohn, R. (ed) *Global Warming and the American Economy: A Regional Analysis*, England: Edward Elgar Publishing pp.106-131..

IPCC (Intergovernmental Panel on Climate Change). 2007a. *The Physical Science Basis,* Cambridge University Press, Cambridge UK.

IPCC (Intergovernmental Panel on Climate Change). 2007b. *Impacts, Adaptation and Vulnerability,* Cambridge University Press, Cambridge UK.

Kurukulasuriya, P. and R. Mendelsohn. 2007. "Endogenous Irrigation: The Impact of Climate Change on Farmers in Africa" *World Bank Policy Research Working Paper* WPS4278, Washington DC.

Kurukulasuriya, P. and R. Mendelsohn. 2008. “Crop Switching as an Adaptation Strategy to Climate Change” *African Journal Agriculture and Resource Economics* **2**: 105-126.

Lund, J., T. Zhu, S. Tanaka, M. Jenkins. 2006. “Water Resource Impacts” in J. Smith and R. Mendelsohn (eds.) *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California.* Edward Elgar Publishing, Northampton, MA. pp 165-187.

Mansur, E., R. Mendelsohn, and W. Morrison. 2008. “A Discrete Continuous Model of Energy: Measuring Climate Change Impacts on Energy" *Journal of Environmental Economics and Management* **55:** 175-193.

Mendelsohn, R., W. Nordhaus and D. Shaw. 1996. "Climate Impacts on Aggregate Farm Values: Accounting for Adaptation", *Agriculture and Forest Meteorology* **80:** 55-67.

Mendelsohn, R. 2000. "Efficient Adaptation to Climate Change", *Climatic Change* **45:** 583-600.

Mendelsohn, R. and A. Dinar. 2003. “Climate, Water, and Agriculture”, *Land Economics* **79** 328-341.

Mendelsohn, R. 2006. “The Role of Markets and Governments in Helping Society Adapt to a Changing Climate” *Climatic Change* Special Issue on *Climate, Economy, and Society: From Adaptation to Adaptive Management* **78:** 203-215.

Mendelsohn, R., A. Dinar, and L. Williams. 2006. “The Distributional Impact of Climate Change On Rich and Poor Countries” *Environment and Development Economics* **11**: 1-20.

Morrison, W. and Mendelsohn, R.: 1998, ‘The Impacts of Climate Change on Energy Expenditures’ in Mendelsohn, R. and Neumann, J. (eds.), *The Economic Impact of Climate Change on the United States Economy*, Cambridge University Press, Cambridge, U.K.

Neumann, J., and N. Livesay. 2001. “Coastal structures: Dynamic economic modeling” in Mendelsohn, R. (ed) *Global Warming and the American Economy: A Regional Analysis*, England: Edward Elgar Publishing, pp132-148.

Ng, W. and R. Mendelsohn. 2005. “The Impact of Sea-Level Rise on Singapore” *Environment and Development Economics* **10:** 201-215.

Ng, W. and R. Mendelsohn. 2006. “The Impact of Sea-Level Rise on Non-Market Lands in Singapore” *Ambio* **35:** 289-296.

Rosenthal, D., H. Gruenspecht, E. Moran. 1995. Effects of global warming on energy use for space heating and cooling in the United States, *Energy Journal* **16:** 77–96.

Samuelson, P.: 1954, ‘The Pure Theory of Public Expenditures’, *Review of Economics and Statistics.* **36**, 387–389.

Schelling, T. 1992. “Some Economics of Global Warming” *American Economic Review* **82**: 1-14.

Seo, N. and R. Mendelsohn. 2008a. “Climate Change Impacts on Latin American Farmland Values: The Role of Farm Type” *Revista de Economia e Agronegocio* **6**: 159-176.

Seo, N. and R. Mendelsohn. 2008b. “An Analysis of Crop Choice: Adapting to Climate Change in Latin American Farms” *Ecological Economics* **67:** 109-116.

Seo, N. and R. Mendelsohn. 2008c. "Measuring Impacts and Adaptation to Climate Change: A Structural Ricardian Model of African Livestock Management" *Agricultural Economics* **38**: 150-165.

Seo, N., R. Mendelsohn, P. Kurukulasuriya, and A. Dinar. 2009. “An Analysis of Adaptation to Climate Change in African Livestock Management by Agro-Ecological Zones” *B.E. Journal of Economic Analysis & Policy* http://www.bepress.com/bejeap/vol9/iss2/art4

Seo, N. B. McCarl, and R. Mendelsohn.2010a. “From Beef Cattle to Sheep under Global Warming?: An Analysis of Adaptation by Livestock Species Choice in South America” *Ecological Economics* **69**: 2486-2494.

Sohngen, B. and R. Mendelsohn. 1998. “Valuing The Market Impact of Large-Scale Ecological Change: The Effect of Climate Change on US Timber", *American Economic Review* **88:** 686-710.

Sohngen, B., R. Mendelsohn and R. Sedjo. 2002. "A Global Model of Climate Change Impacts on Timber Markets" *Journal of Agricultural and Resource Economics* **26:** 326-343.

Tol, R., Fankhauser, S., and Smith, J.: 1998, “The Scope for Adaptation to Climate Change: What Can We Learn from the Impact Literature?” *Global Environmental Change* **8**, 109–123.

United Nations Framework Convention on Climate Change (UNFCCC). 2007. *Climate Change: Impacts, Vulnerabilities, and Adaptation in Developing Countries.* Bonn, Germany.

Wang, J., R. Mendelsohn, A. Dinar, J. Huang, 2010. “How Chinese Farmers Change Crop Choice To Adapt To Climate Change” *Climate Change Economics* **1**: 167-186.

World Bank. 2010. T*he Economics of Adaptation to Climate Change.* Washington DC.

Yohe, G., J. Neumann, P. Marshall 1999. The economic damage induced by sea level rise in the United States. In R. Mendelsohn and J. Neumann (eds) *The Impact of Climate Change on the United States Economy*. Cambridge University Press, Cambridge, UK.