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THE ECONOMICS OF ADAPTATION TO CLIMATE CHANGE IN DEVELOPING COUNTRIES

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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 the various 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, for example, by building sea walls to protect from inundation, and seizing new opportunities, for example, by growing in crops in places that were previously too cold. Research must now focus on making the practical steps that turn that potential into reality.

Keywords: Climate Change Adaptation; developing countries; public adaptation; private adaptation.

1. Introduction

The extent of climate change that will occur in the future will depend on the extent of mitigation that the global society finally agrees to do and how natural systems adjust to rising greenhouse gases (IPCC, 2007a). Given the high cost of mitigation and the difficulty in making aggressive changes to our emission path, it is highly likely that the emission levels of greenhouse gases will continue to rise. Societies around the world will very likely face some additional climate change in the years to come. What is not known is the extent to which climate will change. Current estimates of global temperature change range from 1.5°C to 5.4°C by 2100 (IPCC, 2007a). The range of potential changes in local temperature is even greater, but every society will be affected. Every country must confront what they should do to adapt to climate change.

Adaptation is any change in behavior or capital 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 in each place, how 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 (Mendelsohn, 2000). That is, the additional benefits of all efficient adaptations are greater than their cost. Not every adaptation to climate is efficient. For example, building a sea wall that costs $5 billion to protect land that is worth $1 billion is not efficient. Building a canal that costs $1 billion to irrigate cropland worth only $500,000 is not efficient. Society must evaluate all the changes they can do to "climate proof" themselves and select only the efficient options. Only adaptations whose benefits exceed the cost should be undertaken. Adaptation projects with high costs and low benefits actually make the climate problem worse by increasing the overall cost to society of climate change. Whether any specific adaptation 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, Dinar and Williams, 2006). 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 have other burdens as well. They tend to have a disproportionate share of their GDP in climate-sensitive sectors (especially agriculture). They will consequently experience higher impacts as a fraction of their GDP. They also 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. Lacking public infrastructure and critical institutions, many developing countries also lack the foundation to support strong markets. For example, the absence of enforced property rights will discourage many private actors (firms and households) in developing countries from adapting efficiently. All of these problems combine to suggest that developing countries will bear the brunt of climate change damage.

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 emissions 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.

2. Theory of Efficient Adaptation

2.1. *Private adaptation*

If the consequences of an adaptation decision affect only the decision maker, we define these actions as "private adaptation". With both firms and households, many adaptation decisions involve only their own welfare; they are private adaptations. The costs and the benefits of private adaptation accrue just to the firm or household. Because the decision makers are interested in maximizing their own welfare, the only adaptations they will choose are ones that make them better off. Firms and households will choose efficient adaptations. Of course, this assumes access to markets, private property rights, no externalities and good information, all of which we discuss further in the paper.

2.2. *Household 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 simple 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):

$$\text{Max}\, U(X, C) \quad s.t.\ Y = PX, \tag{1}$$

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

$$\begin{aligned} X_1 &= D_1(P, Y, C), \\ X_2 &= D_2(P, Y). \end{aligned} \tag{2}$$

For a vector of goods, X_2, C will not play any role. The desire for many goods such as transport or staples may not be climate sensitive. Households will purchase the same amount of these goods (given a market price and their income) no matter what the climate is. However, for another vector of goods, X_1, C will shift the demand function. For example, households may want more water to drink or lighter clothing in a warmer climate. Given the price of water or clothing, they will decide to buy more or less of these goods as climate changes. 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, it is likely that households will quickly learn whether they want to change their behavior as they experience a new climate.

Some of the decisions by households involve buying capital goods such as shelter. 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.

$$\text{Max} \int U_t(X, C, K)e^{-rt}dt \quad s.t. \int [Y_t - P_x X_t]e^{-rt}dt - P_k K = 0, \tag{3}$$

where the asset is bought at the start of the analysis. Taking the first-order condition of (3), each household will equate the price of capital (P_K) with the present value of the resulting stream over time of marginal utility (dU_t/dK):

$$P_K = \int dU_t(X, C, K)/dKe^{-rt}dt. \tag{4}$$

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, a household may want more shelter if there is more rain. However, the household is concerned with the present value of the stream of benefits. If the benefits occur far into the future, the present value will not increase much. People will have a larger response to more imminent changes in climate. For example, they are not likely to buy more shelter today in anticipation of an increase in rain in 40 years.

There is another important difference between capital investments and annual consumption. Annual consumption is easy to adjust. Consumers can wait and see how climate unfolds before changing their behavior. However, capital investments have long time horizons. The consequences of capital investments last for decades. Consumers making capital adjustments must anticipate how the climate is going to change over the lifetime of the investment. Uncertainty about the magnitude of future climate change makes it difficult to adapt in advance. Anticipatory adaptation is done under a cloud of uncertainty. Because the future state of climate is not known, people will be reluctant to make as much adaptations as they would under perfect information. Capital is also not easy to adjust once it is purchased. Adaptations involving capital are likely to be much slower than adaptations involving daily consumer purchases. The more rapidly that climate changes, the more likely capital adjustments will lag behind climate change. This is especially true if the speed of climate change is a surprise.

One suggestion in the literature is that insurance companies can provide insurance for households against climate change. Whereas insurance for weather events is a common feature of many insurance contracts, none of these contracts are long–term climate contracts. Insurance companies renegotiate contracts for weather each year. As weather changes over time, premiums also change. To eliminate the climate uncertainty facing households, insurance contracts would have to be written for decades, not a single year. Companies would have to promise to make payments every year for climate outcomes into the distant future to eliminate the risk to the household of climate uncertainty. However, unlike weather events, which will vary from one household to another, climate uncertainty is correlated across many households. In the extreme, the entire earth will experience a certain amount of warming. The uncertainty for the insurance company is not a set of small independent risks but rather one very large risk. The insurance industry is simply not large enough to offer such policies.

2.3. *Firm adaptation*

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

$$\text{Max}\,\pi = P_Q Q(Z, C) - \Sigma P_Z Z, \tag{5}$$

where P_Q represents the price 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 first-order condition for the firm is to equate the price of each input to its marginal productivity:

$$P_Z = dQ(Z, C)/dZ. \tag{6}$$

Climate affects the marginal productivity of selected industries such as agriculture and forestry. As climate changes, firms will experience either productivity increases or decreases. This will cause them to change their inputs as the marginal productivity of these inputs change. In certain circumstances, it may cause firms to shift their output as well. For example, if warming makes one output much less profitable than another, they likely will shift to the new more profitable output. For example, farmers may shift which crop to grow or which animal to raise with climate change.

The effect of climate on production 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, the relationship between coastal structures and sea level rise is more monotonic with increases in sea level strictly increasing damages.

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:

$$\text{Max} \int [P_Q Q_t(Z, K, C) - \Sigma P_Z Z_t] e^{-rt} dt - P_k K, \tag{7}$$

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 present value of the stream of marginal productivity gains over time:

$$P_k = \int P_Q \partial Q_t(Z, K, C)/\partial K e^{-rt} dt. \tag{8}$$

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 for capital-intensive sectors such as the coastal (sea level rise) and forestry sectors. As with consumers, capital decisions involve benefits accruing far into the future. Firms consequently face the same uncertainty as households concerning how climate will change. They too will probably provide less anticipatory (planned) adaptation because of this uncertainty than they would under perfect information.

2.4. *Public adaptation*

With some decisions, however, many people are affected by a choice. For example, building a sea wall across a coastline protects everyone behind it. Saving an endangered species benefits everyone who cares about biodiversity. Building a road gives everyone along the road access. Protecting property rights gives everyone in a society an incentive to invest in capital. Because such decisions affect many beneficiaries, we define them as "public adaptations". The efficient amount of public adaptation maximizes net aggregate benefits:

$$\text{Max } \Sigma B_i(Q) - C(Q), \tag{9}$$

where $B_i(Q)$ is the benefit to each household (i) 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. Maximizing with respect to Q yields the following first-order condition:

$$MC(Q) = \Sigma MB_i(Q). \tag{10}$$

The optimal amount of public adaptation equates marginal cost with the sum of marginal benefits across all individuals. 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 (e.g., clubs). However, when consumers are heterogeneous, it is difficult to coordinate collective payments and public goods are underprovided. Markets are not effective at providing public adaptations. They have difficulty collecting payments from the disparate beneficiaries. Public adaptations require government involvement to succeed.

Governments consequently have a critical role to play in adaptation to make sure that public adaptations are done efficiently. 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 can work efficiently 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 at providing public goods. 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.

There is a reason to be especially 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 over-adapt to benefit a few chosen citizens and under-adapt to benefit everyone else. They are likely to be less informed about their choices and the ramifications. There may be a strong need for international governmental organizations to assist local and national governments in developing countries to design and implement public adaptation.

2.5. *Poverty*

Another important topic is the role of poverty in adaptation. Poor individuals and small firms may make different decisions 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. Poor individuals may lack access to credit markets and so they effectively face higher interest rates. However, it is not necessarily true that wealthy families will find it easier to adapt to climate change than poor families. The outcome for each household will depend on the extent that climate affects it and what alternatives are available. For example, a poor family that is barely affected by climate will not have much adaptation to do. Some poor families may have many inexpensive alternatives to adjust to climate change. In contrast, some wealthy families may have specialized in goods and services that are tied to a temperate climate and so they can be more vulnerable to climate change than poor families more reliant on goods and services based on a tropical climate. It is an empirical question whether poor versus wealthy families will be more vulnerable.

Governments and NGOs 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. Providing access to capital markets and secure property rights should be 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. Assisting with private adaptation can be quite difficult because the third party (government or NGO) must be informed about the local conditions and desires of the targeted audience (the poor people). 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 on each program but the improvement in welfare of the targeted population. However, this problem is not peculiar to climate change adaptation, it is relevant to development and social programs as well.

2.6. *Market adaptation*

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 outward (inward). The good will become more (less) scarce and prices will increase (decrease). The change in price will in turn cause suppliers to react. With higher (lower) prices, suppliers will 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 consumers 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 adapt, the impacts of climate change are felt throughout the world, not just in the places where the direct impacts first occurred.

2.7. *Anticipatory adaptation and uncertainty*

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). With perfect information, 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 perform 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). Of course, actors should perform advanced planning. But, 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. Therefore, it is likely that the bulk of adaptation will be reactive. Capital investments, by their long-term nature, will always require some anticipation. But it is not likely (or even desirable) that people will fully adapt in advance (given climate uncertainty).

2.8. *Market failure*

A common theme in development economics concerns market failures. For example, firms and households 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 (Ostrom, 1990), they tend to involve very low levels of investment into the land and occur only in special circumstances. In contrast, problems with common property resources abound in cropland, grazing, forestry and fisheries (Hardin, 1968). Common property tends to lead to underinvestment in 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 underinvest in a place 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.

Another frequent problem is lack of access to markets. For rural inhabitants, especially in the least developed countries, poor transportation infrastructure may make market access prohibitive. This prevents farmers from selling their products in markets but also prohibits them from getting access to inputs such as fertilizer or electricity. These problems can lead to distorted prices which differ from the desired shadow price (Dasgupta *et al.*, 1972). Rural inhabitants also may lack access to capital markets so that they face higher interest rates and make fewer capital investments (Little and Mirrlees, 1974). Finally, rural households may lack access to information and so make many decisions in ignorance. Correcting these market problems can lead to win-win solutions in that they provide benefits without climate change and they also facilitate better climate adaptation decisions.

2.9. *Development as climate adaptation*

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. The more wealth and income is in sectors that are insensitive to climate, the more climate-resilient is the economy.

Development is also generally helpful because it raises incomes. As people become wealthier, they will pay more for the provision of nonmarket services. That is, richer citizens will pay more for public adaptations to climate. 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.

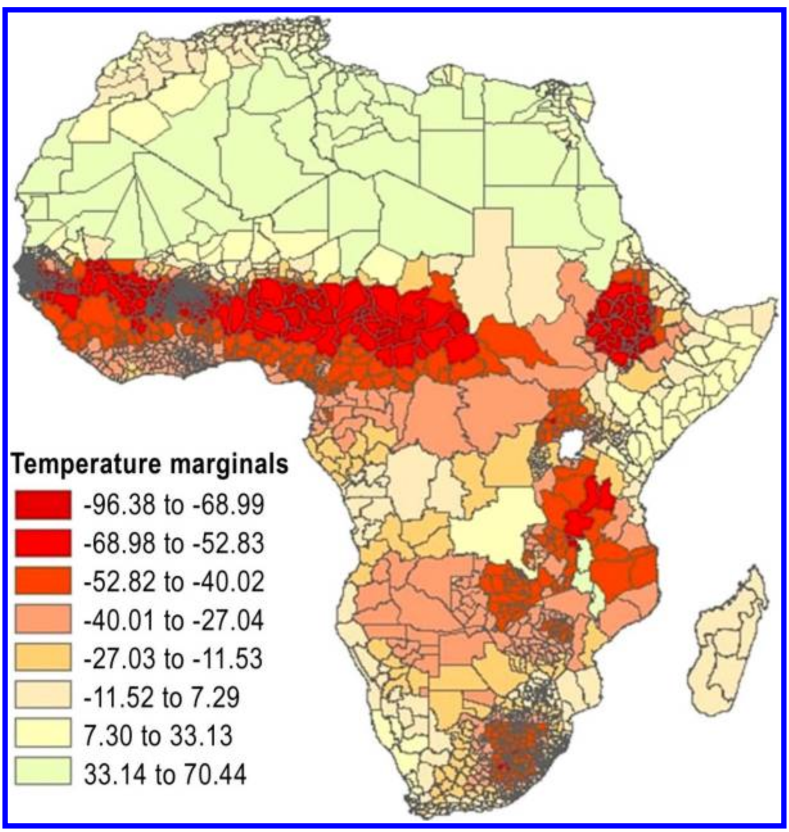
3. Empirical Adaptation

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. For example, one could examine the change in global temperature over time with the change in global crop yields (Lobell and Field, 2007). Unfortunately, there has been so little climate change to date, that the intertemporal record is dominated by nonclimate factors such as economic development, price changes and even technological change. For example, the changes in temperatures and carbon dioxide concentrations from 1960 to 2000 have caused a net global increase in agricultural GDP of about 2% to 4% which explains about 3% to 5% of the total change in agricultural production (Mendelsohn, 2007). It is very difficult to detect such a subtle impact of climate against the backdrop of other dramatic changes happening in agriculture using just intertemporal data. The intertemporal record of climate impacts may be more convincing in the future as climate change progresses, but it does not yet provide a strong signal.

An alternative place to look for empirical evidence on adaptation 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 the current local climate, the regression provides insight into what must be done 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.

A detailed analysis of climate impacts and adaptation reveals that climate change causes a mosaic of changes across the landscape. For example, as shown in Fig. 1, the marginal impacts of temperature across Africa vary a great deal across the continent



Source: Kurukulasuriya *et al*. (2006).

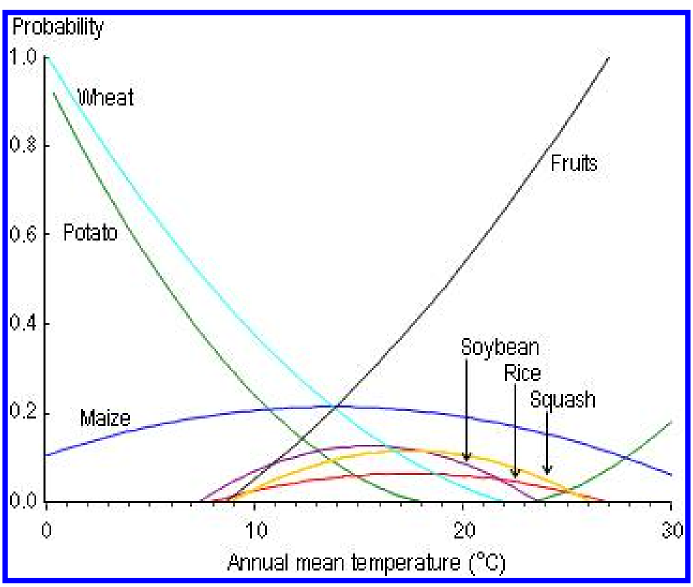
Figure 1. Marginal change in net revenue ($) per hectare with respect to temperature in Africa.

from mildly beneficial in the Sahara Desert and Southern Africa to very harmful in the Sahel and East Africa regions. Adaptations must reflect these widely varying local conditions and will also have a mosaic distribution across space.

3.1. *Agriculture*

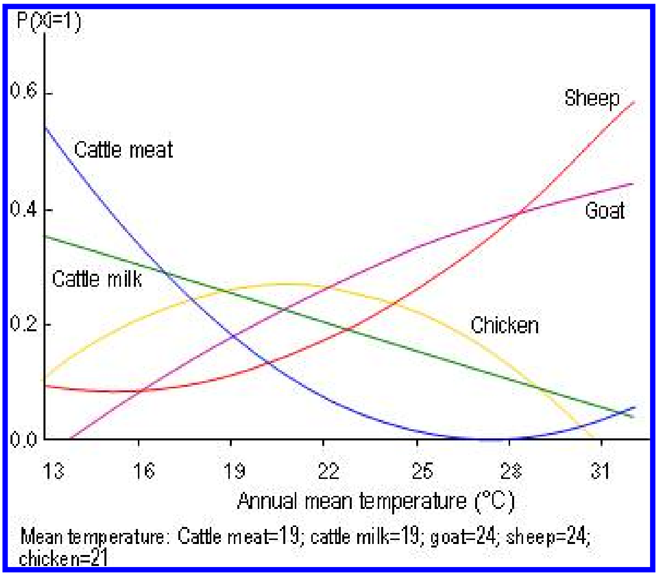
In agriculture, the amount of land that is farmed is sensitive to climate. Controlling for other factors, Mendelsohn *et al*. (1996) find that US farmers are more likely to farm a hectare of land in moderate temperatures. With moderate warming, the increase in farmland in the northern US offsets the decrease in farmland in the southern US. 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 US, the amount of farmland may drop (increase) immediately as climate warms. Whether farmland is used for crops or liverstock can also vary with climate (Seo and Mendelsohn, 2008a).

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 increase (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 increase (see Fig. 2). 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 increase (Wang *et al*.,



Source: Mendelsohn and Dinar (2003).

Figure 2. Probability of crop choice versus temperature in South America.



Source: Mendelsohn and Dinar (2003).

Figure 3. Probability of livestock choice versus temperature in Africa.

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. As shown in Fig. 3, 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 *et al.*, 2010). Their choice of pigs depends upon their current climate.

In general, the marginal productivity of inputs (fertilizer, machinery, expensive seeds, etc.) is higher in 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, Kala and Mendelsohn, 2011). 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.

3.2. *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 from low-valued uses to high-valued uses, however, it is possible to dramatically reduce the damages from runoff reductions. An analysis of the Rio Bravo River predicts climate damages in Mexico can be reduced substantially by reducing low-valued uses (Mendelsohn, 2008). Farmers can also adjust to warmer and drier conditions by adopting water saving technology such as sprinklers and drip irrigation (Mendelsohn and Dinar, 2003; Dinar *et al.*, 2011).

3.3. *Coastal sector*

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 sea levels 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; Neumann 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.

3.4. *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 (fewer) 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.

3.5. *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 climate dominated by cold (heat), warming would be a benefit (damage). In a temperate climate, the total BTUs used would be unchanged (Rosenthal *et al.*, 1995). However, cooling is more expensive than warming, so although the total BTUs might not change, the costs of staying comfortable will increase even in temperate climates (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 that 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 toward 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.

3.6. *Health*

Climate is expected to make three changes that could affect human health: Vector-borne diseases, heat stress and ozone formation (IPCC, 2007b). 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.

3.7. *Conservation*

Quantitative ecological models are quite clear that climate change will alter ecosystems worldwide (VEMAP, 1995; IPCC, 2007b). 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 that 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 (Cramer *et al.*, 2001). These studies have examined how ecosystems have changed in the past in reaction to large global forces such as 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 toward 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 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.

3.8. *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 (UNFCCC, 2007) to \$75–\$100 billion (World Bank, 2010). However, these estimates are likely biased upward 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 adapting 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. This is especially true for changes in precipitation patterns.

4. 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 costs. The literature has noted important distinctions between private and public adaptation. Private actors will generally adopt efficient private adaptations without public policy interventions.

However, there are important exceptions where markets may fail to provide efficient adaptations to climate change. With common property, poorly protected private property rights, and externalities, private adaptation will often be inefficient. These problems require institutional (governmental) responses to create desirable private incentives. National governments, and especially national governments in developing countries, can lay a solid foundation for private adaptation by converting commercially valuable common property into private property and by protecting existing private property rights. Work still needs to be done to determine what land should be privatized and exactly how the process of conversion should be designed. Finally, national governments can improve the management of externalities by "getting the prices right"; using taxes and regulations to encourage private actors to take into account the damages they impose on the environment. All of the above institutional improvements are "win–win" strategies in that they would make society better off even without climate change.

Another critical insight of the theoretical literature is that markets will underprovide public adaptations, where there are many beneficiaries of an action. Local and national governments must directly manage public adaptations. Specifically, they must capture the interests of the multiple beneficiaries of public goods; paying the aggregate demand for these goods in the market. This may be particularly difficult for the local and national governments of developing and especially least developed countries.

These governments lack the financial resources and technical expertise to carry out these functions efficiently. International aid and intergovernmental agencies have an important role to assist least developed local and national governments to provide public adaptations. Public adaptations include coastal protection, public health responses and conservation measures. Public adaptations also include improved technologies suited for warmer climates (research and development) and improved measurement and forecasting of climate change. For example, research and development into new crop varieties and breeds may give farmers important new choices. More accurate measures of current weather and better forecasts of future weather can improve anticipatory (planned) adaptation.

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 the literature is just beginning to reveal what choices farmers should exercise in some places and some moments in time. Current research in Africa, Latin America and China suggests that farmers should adjust whether to grow crops or livestock or both, what crops to grow, what animals to raise, and what inputs to employ. The pattern of adaptation 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. Other vulnerable sectors must also adapt. Water should be reallocated from low-valued to high-valued uses. Additional capital investments in the water sector may also be needed. Dams could store early winter melt for valuable growing season irrigation. Levees could control flooding. New canals could open up more land for irrigation. Coastal structures should be built to protect valuable developed coast lines from sea level rise. When they should be built and how high they should be needs to be determined. Forests need to be adapted to changing ecological conditions. Harvesting, planting and fire policies may all need to be revised to take into account ecological changes from climate change. As incomes change in developing countries, there is going to be a large increase in cooling demand. Coupling this with warming will lead to a dramatic increase in investments into insulation and cooling capacity. Least developed nations, in particular, need research on private adaptation to better understand what changes climate change will bring.

But perhaps what needs the most attention in adaptation research 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?

One of the factors inhibiting anticipatory (planned) adaptation is the large uncertainty surrounding forecasts of climate change. Local actors need to know how their local climate is likely to change over the next few decades. Climate models currently predict a wide range of local temperature and especially precipitation changes. Actors are consequently discouraged from making many anticipatory adaptations because their benefits are highly uncertain.

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

One final note worth making is that development itself is a form of adaptation for most developing countries. Development encourages "agrarian" economies to move toward more balanced economies. Because the new sectors that will grow under development tend to be much less climate sensitive, development reduces the vulnerability of agrarian economies to climate change. Further, it is extremely difficult to administratively separate development from adaptation policies (i.e., to determine additionality). Policies that merge development and climate adaptation into a single cohesive program would be far more effective than policies which keep these two efforts separated.

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