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Featured Article

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Abstract *Even though much has been written about climate change and poverty as distinct and complex problems, the link between them has received little attention. Understanding this link is vital for the formulation of effective policy responses to climate change. In this article the authors focus on agriculture as a primary means by which the impacts of climate change are transmitted to the poor and as a sector at the forefront of climate change mitigation efforts in developing countries. In so doing, they offer some important insights that may help shape future policies as well as ongoing research in this area.*

JEL codes: Q24, Q27, Q54, Q56, O13, O15.

Climate change is a "wicked problem." We use this terminology in the spirit of Sandra Batie's recent Agricultural and Applied Economics Association (AAEA) Fellows Address (Batie 2008). In her paper, "wicked" problems contrast with "tame" ones for which the definition is clear and the outcome is definitive. Tame problems may be readily identified as either solved or not solved. However, in the case of climate change, there is little agreement on an appropriate definition of the problem—let alone the appropriate solution. And, while economics has played an important role in assessing climate impacts and alternative mitigation strategies, successful involvement by economists in the analysis of climate change requires broad engagement with other disciplines and with society at large (Toman 2006)—hence the complexity of this problem.

To date, most economic analyses of climate change impacts and mitigation have focused on aggregate costs and benefits. Many of those nations most likely to be severely affected by climate change are characterized by extreme poverty. Fortunately they are also located in regions of the world with some of the greatest potential to contribute to mitigation—particularly for forest carbon sequestration, but also through agricultural practices. This leads us to wonder: what are the potential consequences of climate change for the poor? This is a question that has received relatively

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little attention in the literature to date. Our article seeks to shed light on this important problem, focusing specifically on the links from climate change, through agriculture, to poverty.

As Fischer, Shah, and van Velthuizen point out, nearly 800 million people in the world are chronically undernourished and poor—a large portion of them children under the age of five. In sub-Saharan Africa—one of the regions deemed most vulnerable to climate change—poverty rates reach a staggering 40 percent of the entire population (Fischer, Shah, and van Velthuizen 2002). The majority of the poor live in rural areas where agriculture is the predominant form of economic activity; their fate is thus inextricably interwoven with that of farming. Agricultural (GDP) growth is 2.2 times as effective at reducing poverty, compared to growth in non-agricultural GDP (Christiaensen, Demery, and Kühl 2006). However, agriculture—particularly in the tropics—is one of the sectors that is most vulnerable to climate change (WDR, p. 5). The poor are also extremely vulnerable to increases in food prices, as demonstrated by the poverty consequences of the recent food price spike (De Hoyos and Medvedev 2009; Ivanic and Martin 2008).

We readily acknowledge that agriculture is not the only means by which climate change can impact on the poor. Potential damage to infrastructure such as roads, public and commercial buildings, and housing due to natural disasters may have localized, adverse impacts for the population as a whole. Likewise, disease, conflicts over scarce natural resources, or ethnic strife exacerbated by migration away from vulnerable, low-lying areas may have a profound and adverse impact on the poor (Barnett 2001; Heltberg, Jorgensen, and Siegel 2008; Morton 2007; Raleigh, Jordan, and Salehyan 2008; Reuveny 2007). By focusing exclusively on agriculture, our treatment of the poverty impacts of climate change necessarily understates their true extent. However, analysis of the climate change-agriculture-poverty nexus yields valuable insights for climate change mitigation efforts and development policy, which are best understood when examined in a focused manner.

How will future changes in climate affect these low income households? What is the likely impact on the price for food—the single largest budget item for most of the poor? In order to answer these questions, we knit together research from a variety of disciplines and different perspectives. While there is much more work to be done in this area, sufficient research is already available to allow us to reach some preliminary conclusions about the potential impacts of climate change and associated policies on agriculture and hence on poverty. First we touch on the likely changes in climate caused by increased concentration of Greenhouse Gases (GHGs) in the atmosphere. Here we will be brief, as current knowledge is well summarized by the Intergovernmental Panel on Climate Change (IPCC) (Parry et al. 2007). We then move on to the question of how such changes in climate are likely to affect agricultural productivity. This is a rapidly growing literature, which is grudgingly yielding some consensus. There remain large differences, however, in the various scientific approaches to the problem, each with its own strengths and limitations. Accordingly we provide readers with a critical evaluation of this literature.

Having assessed the likely impact of climate change on agricultural productivity, we face the challenge of understanding how such productivity shocks are likely to affect poverty and vulnerability of low income households. We draw on prior research examining the impacts of historical climate events—including droughts, floods, etc.—on poverty. This rich literature offers some important insights into the kinds of policies which might limit the adverse impacts of climate change and climate shocks on the poor. This literature also naturally leads into the broader question of adaptation and dynamics: Given the inevitability of increased GHG concentrations in the atmosphere and the consequent changes in climate, what policy measures can be taken to ensure resiliency throughout the economic system and attenuate the damaging impacts on the poor in particular?

Despite the lack of immediate action flowing out of the recent climate change summit in Copenhagen, there is already significant spending underway, aimed at the mitigation of GHG emissions, with much more effort likely to follow. Thus it is important to explore the potential consequences of such mitigation policies—particularly those that impinge on land use—for agriculture, food prices, and poverty. Finally we conclude with a discussion of the overarching policy implications.

Climate Change: What is the Evidence?

There is now little doubt that the climate is changing; carbon dioxide (CO_2) concentrations in the atmosphere are rising, as are temperatures (IPCC). Yet detection of climate change and the attribution of its causes are distinct problems. Without the capacity to conduct repeated experiments with the earth's climate, researchers resort to models as a means to illuminate the link between these changes to human (anthropogenic) forcings. The IPCC has done so by running the community of climate models over the last century, first with only natural forcings, and then with both natural and human forcings. The resulting confidence intervals for predicted temperatures over the past two decades show significant differences between the evolution of climate under the baseline and the (natural forcings only) counterfactual (IPCC). Based on this link, it is then possible to project future changes in climate as GHG concentrations in the atmosphere grow over time. Under its baseline projection, the IPCC projects further global warming of 1.1 to 6.2°C by the end of this century (IPCC). The models also consistently show that increases in GHG concentrations cause increases in both the frequency and the intensity of temperature and precipitation extremes (Ahmed, Diffenbaugh, and Hertel 2009; Easterling et al. 2000). These changes in climate volatility are likely to be particularly important for agricultural systems, which can be quite sensitive to such extremes (White et al. 2006).

For this survey, we are less concerned with the attribution aspect of the climate debate and more concerned with the implications of detected changes—whatever their cause. What are the likely *impacts* of rising temperatures and changing rainfall patterns on agriculture and poverty? Of these changes, can we deduce which effects will have the largest implications for poverty?

Agricultural Impacts of Climate Change

Tubiello and Rosenzweig (2008) survey the rather extensive literature on the agricultural impacts of climate change and offer a useful synthesis

(p. 167). They conclude that moderate warming (up to 2°C) in the first part of this century may benefit crop and pasture yields in the temperate regions, while reducing crop yields in the semi-arid and tropical regions. However, the further warming that is expected for the second part of the century will likely reduce crop yields in *all* regions.

Taking a user's perspective on what is now a vast literature on the potential agricultural impacts of climate change, it is important to understand the different approaches that have been taken to estimate these effects as they reflect sharply different "views of the world." We group the approaches into three categories: crop growth simulation models, statistical studies, and hedonic (or Ricardian) approaches. Each approach embodies rather different strengths and weaknesses as measured by the following criteria (Rowhani and Ramankutty 2009):

- How onerous are the data requirements?
- What is the spatial extent of the methodology—i.e. can it be used to predict global impacts? Is it portable across regions?
- Spatial resolution—i.e. can the predictions be related to specific grid cells on the earth's surface?
- Is this methodology process based?
- What is the potential for capturing threshold effects?
- Can it capture adaptation responses to climate change?
- Can the model's validity be tested via out of sample validation?

Crop growth simulation models

The predominant tool for assessing the impacts of climate change on agricultural productivity is the biophysical crop growth simulation model. The most widely used variant for climate change analysis is the Crop Environment Resource Synthesis model, as implemented through the Decision Support System for Agrotechnology Transfer (DSSAT). DSSAT underpins a number of important studies of the impact of climate change on global food availability and malnutrition, including (most recently) Nelson et al. (2009). Those authors find climate-induced changes in 2050 developing country yields ranging from 1 percent in the case of rainfed rice and wheat to 19 percent for irrigated rice and 34 percent for irrigated wheat (Nelson et al. 2009, table 2).

DSSAT covers six major field crops. It is a process-based model with extensive data requirements and explicit spatial resolution, simulating crop growth as a function of soils, water availability, temperature, and soil nitrogen dynamics at the level of an individual field. Crop growth is broken into six phenological stages and leaf and stem growth rates are calculated for each stage. Management factors are also considered, including choice of variety, planting date, row spacing, and irrigation and nitrogen fertilizer application amounts and timing. By varying temperature and precipitation inputs, users can simulate the impact of climate change on agricultural productivity.

Important strengths of crop simulation modeling include: (a) the simulation of growth by stage so that daily temperature data can be utilized and the impact of extreme events on yields can be assessed, and (b) the ability of users to specify crop varieties and fertilizer applications, as well as irrigation availability, all of which are critical elements in any climate adaptation strategy. However, despite its use in global studies, the DSSAT approach remains fundamentally a highly calibrated, field-based approach which has not yet been validated on a global basis.

This limitation has stimulated new work by Deryng, Sacks and Ramankutty (2009) who have developed a simpler, less highly calibrated variant of the crop simulation model, nicknamed Agro-PEGASUS. It has been designed to operate at a global scale and simulates growth as a function of light use efficiency, daily average absorbed photo synthetically active radiation, temperature, soil moisture, and fertilizer availability. It has also been validated at that scale.

Agro-PEGASUS model predictions for planting and harvest dates for global maize area agree with observed ranges in about three-quarters of all grid cells where maize is grown. Predicted global maize yields also compare reasonably well to actual yields. For a 2°C rise in global temperatures, the authors find that average maize and soybean yields rise in high income countries, while falling slightly for wheat (Deryng, Sacks and Ramankutty 2009). The lowest income countries experience the sharpest yield losses, ranging from −13 percent for spring wheat to −22 percent for soybeans and −27 percent for maize. From the point of view of poverty, this is not a good outcome. It suggests lower farm incomes in the poorest countries (due to the sharper productivity reductions there) where extreme poverty tends to be predominantly rural, with somewhat higher world prices overall, thereby hurting low income consumers worldwide. While Agro-PEGASUS is not yet available to the broader research community, it is a tool worth keeping an eye on for future research.

Statistical approaches

An alternative to the crop simulation approach is to estimate statistical relationships between crop yields on the one hand and temperature and precipitation on the other. The advantages of this approach are that it requires relatively less data and can be readily implemented for large geographic areas (e.g. nations or continents). However, it is not process based, and so it relies on predicting future responses based on past relationships. Thus changes in varieties grown, and other agro-ecological choices, such as planting and harvesting dates, etc., are not taken into account. Recent examples of this approach are offered by Schlenker and Roberts (2006), Lobell et al. (2008), and Schlenker and Lobell (2010).

Statistical studies can be based on cross-sectional data or time series data. The former naturally correspond to longer run adaptations to climate. The problem with cross-section analysis, however, is the potential for omitted variables to bias parameter estimates. An excellent example of this is offered by Schlenker, Hanemann, and Fisher (2005) who show that, if irrigation is not explicitly taken into account and irrigation tends to take place in hotter regions, then yields (economic returns) might appear to be positively related to temperature when in fact this is not the case.

Time series approaches analyze the impact of year-to-year changes in climate on yield variation at a given site. This technique estimates the short-run impact of climate change on yields assuming the climate change was not fully anticipated (e.g. the climate realization occurs after planting decisions are already made). Recently, McCarl, Villavicencio, and Wu (2008) have used time series methods to examine the impact of climate variability on crop yields. Those authors find that, for the United States, higher variances in climate conditions tend to lead to lower average crop yields and also greater yield variability (p. 1247). However, in most regions of the world, time series on yields and climate are limited in length, thereby resulting in large standard errors and significant uncertainty about the likely impacts of temperate and precipitation on yields. As a consequence, Schlenker advocates panel data approaches in which a cross-section of yields is followed over time, using fixed effects to account for location-specific determinants of yields.

Generally these crop response studies show that maize and other coarse grains have the greatest potential to be adversely affected by climate change. This is due to the low responsiveness of C_4 crops to increased CO_2 concentrations (Ainsworth et al. 2008; Long et al. 2006) and their relatively high sensitivity to extreme heat (Schlenker and Lobell 2009; Schlenker and Roberts 2006).[1] Indeed, in their study of maize response to temperature in the northeastern United States, Schlenker and Roberts identify a clear threshold at 30°C, after which additional increments to temperature result in a sharp reduction in yields. This type of nonlinearity can have important consequences in the case where climate change leads to an increase in the intensity and frequency of extreme heat events, as suggested by Easterling et al. (2000). This predicted sensitivity of maize to high temperatures is also consistent with the finding of Lobell and Field (2007) that maize yields since 1980 have been adversely affected by global warming. On the other hand, the impacts of climate change on yields of wheat and rice (C_3 crops) varies more widely, with the possibility of large yield gains in northern latitudes under global warming. In a recent panel study of the impacts of climate change in 2050 on sub-Saharan Africa, Schlenker and Lobell (2010) find that maize is most severely affected and millet the least affected by climate change. Nearly all countries in the region experience yield losses in the expected scenario, with overall losses for cereals and oilseeds in the range of 10 percent; in the worst case outcome (5 percent probability), yield losses for most cereals and oilseeds in Southern Africa exceed 50 percent.

The foremost advantages of statistical approaches to analyzing climate impacts on agriculture (see also table 1) are that: the data requirements are much lighter; they can be applied at a national or global spatial resolution; measures of goodness of fit can provide confidence that the model is faithfully capturing historical changes; and out-of-sample prediction can test the model's validity. The greatest limitation of these studies focusing on yield changes is the absence of adaptation responses. One approach is to embed these yield "shocks" in an economic model which then allows for adaptation in the context of profit maximizing responses on the part of representative farmers (e.g. Hertel, Burke, and Lobell 2009). However, it would be attractive to obtain estimates of adaptation alongside the climate impact analysis. This is leads us to the so-called Ricardian, or hedonic, analysis of climate change.

Hedonic approaches

All the yield based studies of agricultural response to climate change assume that the crops continue to be grown in the same locations, thereby

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[1] *Plants are classified as C_3 or C_4 based on the biochemical process by which they convert carbon dioxide into sugar during photosynthesis. Common C_4 plants important to agricultural production include maize, sugar cane, millet, and sorghum. Common C_3 agricultural crops include wheat, barley, potatoes, and sugar beet.*

Table 1 Alternative methods for assessing agricultural impacts of climate change compared

	Methodology		
Characteristics	**Crop growth models**	**Statistical models**	**Ricardian models**
Data requirements	Intensive	Modest	Medium
Spatial extent/portability	Local	Global	Regional
Spatial resolution?	Yes	No	No
Process based?	Yes	No	No
Threshold effects?	Possible	Yes	No
Captures adaptation?	No	No	Yes
Out of sample validation?	No	Yes	Yes

Source: *Adapted from Rowhani and Ramankutty (2009).*

failing to account for potential adjustments in the mix of agricultural activities at any given location. The hedonic approach, popularly known as the "Ricardian" approach, and spearheaded by Mendelsohn, Nordhaus, and Shaw (1994), recognizes that farmers will vary the mix of activities to choose the one yielding the highest return on any given parcel of land. As a consequence, they focus on the impact of climate on land values, not yields.[2] By associating climatic variation in a cross-section of data with variation in land values, researchers aim to estimate the long run economic value of climate and hence the impact of changes in climate, *once adaptation to the new climate has taken place.*

The Ricardian approach has been applied in a wide range of circumstances, including developed and developing countries. Mendelsohn (2009) offers a summary of the findings with individual farm data and with district-level data. His studies of Brazil and India suggest that agriculture in both countries is sensitive to even modest warming. However, within these countries, there is great heterogeneity in the estimated impacts. For example he finds that "the wet eastern region of India would mildly benefit from warming whereas the dry western region of India would suffer large damages. The southeastern region of Brazil would benefit whereas the Amazonian and northeastern region of Brazil would be hurt" (pp. 7 –8).

Mendelsohn, Nordhaus, and Shaw (1994) and Mendelsohn et al. (2007) have also examined the impact of increased interannual variance in climate on land values. They find that the impact depends on the timing of these climatic shocks. If the increased variance is in the spring or summer, it tends to reduce land values, as farmers cannot adapt by changing planting decisions. However, they find that heightened winter climatic variance can actually boost the economic value of land, as farmers can take advantage of these changes by planting different crops and adjusting the growing season.

Analysis at the farm level in Africa shows that warming hurts dry land farming, but benefits irrigated agriculture. These studies also show that

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[2] *The use of land values has the additional advantage of embodying the expectations of returns in a normal year, whereas annual net returns will be influenced to annual random variations in production. However, in many developing countries land markets are insufficiently developed to allow this approach, and so net returns are used.*

temperature affects the choice of cropping vs livestock. Higher temperatures tend to encourage small farmers to shift from cropping to livestock; the returns to both activities fall, but the decline is greater for crops. On the other hand, large livestock producers, who are typically more specialized in beef cattle which are less well adapted to warmer climates, experience sharper losses at higher temperatures.

In wrapping up this survey of a decade of Ricardian analysis in developing countries, Mendelsohn (2009, pp. 16 –17) concludes that:

> The studies generally confirm the hypothesis that tropical and subtropical agriculture in developing countries is more climate sensitive than temperate agriculture. Even marginal warming causes damages in Africa and Latin America to crops. Crops are also sensitive to changes in precipitation. In semi-arid locations, increased rainfall is beneficial. However, in very wet places, increased rainfall can be harmful. If climate scenarios turn out to be relatively hot and dry, they will cause a lot of damage to farms in low latitude countries. However, if climate scenarios turn out to be relatively mild and wet, there will be only modest damages and maybe even beneficial effects. The magnitude of the damage depends greatly on the climate scenario.

The hedonic approach relies on two key assumptions. First, there is a long run equilibrium in factor markets (especially land). Second, there are no adjustment costs such that land rents fully reflect the value of climate at any given location. Given these assumptions, the hedonic approach typically utilizes cross-section data to estimate long-run relationships, which are thus sensitive to omitted variable bias. Schlenker, Hanemann, and Fisher (2005) examine this issue in considerable detail in the context of the Mendelsohn, Nordhaus, and Shaw (1994) findings of warmer temperatures leading to higher economic returns in the United States. These authors show that this finding is a consequence of the omission of a variable indicating whether or not the land is irrigated. Since irrigated land tends to be very productive, and the value of pre-existing water rights (and low prices for water) tend to be capitalized into land values, these high value land rents—typically in high temperature zones—tend to dominate the regression results. Once Schlenker, Hanemann, and Fisher (2005) control for irrigation (by focusing on the non-irrigated lands alone), this relationship disappears and they conclude that U.S. agriculture is likely to lose from climate change.

Quiggin and Horowitz (1999) offer a different critique of the Ricardian approach—focusing on the comparative static nature of the results. They push the Mendelsohn model (Mendelsohn, Nordhaus, and Shaw 1994; Mendelsohn and Nordhaus 1999) to its logical extreme by evaluating the climatic optimum implied by the returns function—i.e. what is the temperature which maximizes agricultural returns in a given location? They find that the optimal values for some of the climate variables are either implausible or nonexistent, leading them to conclude that, while the Ricardian models fit the data reasonably well, they are not well behaved for points lying outside the range of the observed data.[3] Of course, such criticisms could also be applied to many of the statistical analyses of crop yields as well. Once pushed outside the range of observed climate data, they often "fall apart." Users of these estimated yield and return functions need to be aware of these potential limitations which are not inherent in the approach, but rather are determined by the particular empirical

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[3] *In contrast, Darwin critiques the implied agronomic properties of the estimated functions.*

implementation. This type of problem is likely to be most pronounced in cases where one is considering non-marginal changes in temperature and precipitation—either due to short run inter-annual variation in these variables—or due to very long run analyses of climate change.

A further, important critique of the Ricardian approach pertains to its comparative static nature. The dynamics of adjustment from one climate regime to another are ignored—indeed the resulting estimates of climate impacts assume such adjustment costs to be zero. In the words of Quiggin and Horowitz (1999, p. 1044): "The question addressed by Mendelsohn, Nordhaus, and Shaw may be stated as, 'If temperatures were and always had been 5°F higher, what difference would it make to the net social surplus arising from US agriculture?' But the effect of a 5°F change would be very different if the climate were 5°F warmer next year, than if mean temperatures rose by 0.01°F per year over 500 years." Before we probe more deeply into the dynamics of adaptation, it is helpful to establish the linkage between agricultural productivity shocks from climate change and poverty.

Linking Climate Change, Agriculture, and Poverty

Climate change can be either beneficial to agricultural production or adverse in its productivity impacts. For purposes of discussion here, we focus on the adverse shocks. (Positive productivity impacts will have the opposite sign of those discussed below.) The impacts on household well-being depend importantly on the degree to which the household is integrated into product and factor markets. In the most extreme case, wherein the household is entirely self-sufficient and simply consumes what it produces, a 10 percent productivity reduction will translate into a 10 percent reduction in consumption. However, in most cases, households will be at least partially exposed to markets—either through off-farm work (or the hiring of off-farm labor) or through the sale, or purchase, of produce. In this context we can decompose the impacts of climate change on poverty into several parts: impacts on household consumption, impacts on producer income, indirect impacts through factor markets, and impacts through non-priced goods.[4] We discuss each of these in turn, followed by a variety of related issues.

Consumption impacts

To date, most of the discussion about poverty impacts of adverse climate change and agriculture has focused on food availability and/or food prices (e.g. Fischer 2009; Nelson et al. 2009). Reduced food availability and higher food prices stemming from adverse climate change hurt consumers everywhere. All households expend money on food, and higher prices for food unambiguously reduce the level of well-being which they can attain, at a given level of income.

To a first approximation, the household's current food budget share offers a good estimate of the impact of a food price increase on real income. If a family spends half its income on food, and food prices rise by 50 percent, then their real income will fall by about 25 percent (0.5 * 50%),

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[4] *For the interested reader, a mathematical appendix is available from the authors which formally specifies the assertions about household impacts discussed verbally in this section.*

abstracting from second-order effects stemming from price-induced changes in their consumption bundle. Since the poor tend to spend the highest share of their income on food, adverse climate change is expected to have a disproportionately adverse impact on them. Further, these price increases stemming from a decline in agricultural productivity will be felt by all low income households—not just those in agriculture.

Impacts on farm household earnings

In the absence of commodity price changes, adverse impacts on productivity due to climate change will reduce farm earnings (lower output per unit input generates lower profits). These losses are likely to be magnified if farmer-owned inputs are not the only factors of production. For example, if farm-owned inputs account for half of total costs and the prices of purchased inputs are exogenous to agriculture, then, *in the absence of a commodity price rise*, a 1 percent decline in agricultural productivity will result in a 2 percent decline in farm income. This magnification effect arises because farmers cannot share the burden of the adverse productivity change with the suppliers of non-farm inputs. Of course, if the non-farm inputs are not in perfectly elastic supply, then some of the losses will be shared with suppliers of inputs (e.g. fertilizer producers) in the form of lower prices. Because poor households are likely to be less commercialized, this magnification effect will typically be less pronounced for them.

However, the assumption that farm prices will be unchanged in the face of global climate change is unlikely to be valid and is inconsistent with the emergence of regional food deficits. Widespread reductions in agricultural productivity (relative to their baseline realization) will surely result in reduced output and therefore higher prices (again, relative to baseline). The extent of the price rise will depend on the relative price elasticities of commodity supply and farm level demand—and the latter will depend on the scope of the climate shock. If the adverse climate shock is only for one plot of land, then the farm level demand elasticity is likely to be very high indeed—approaching the case of fixed commodity prices as just discussed. On the other hand, if the climate shock affects the entire region, then the farm level demand elasticity will approach the consumer demand elasticity for food, which may be quite small. If the farm level demand elasticity for agricultural products is inelastic (less than one in absolute value, such that a 1 percent rise in prices results in a less than 1 percent decline in demand), then farm producer returns will actually *rise* in the wake of an adverse productivity shock. This makes intuitive sense, since inelastic demands translate into price rises that exceed the proportionate decline in quantity supplied such their product (producer revenue) rises. Furthermore, the size of the ensuing price rise will be larger, the smaller is the farm supply elasticity with respect to price.

So putting the spending and earnings sides together, adverse climate change will hurt farm households unambiguously when they are subsistence producers, when the climate change is localized, or when the farm level demand for their produce is elastic. The welfare loss will be greater, the more important are food expenditures (both purchases and the imputed value of own-consumption) in farm household income, and the more important are commercial inputs in production. Conversely, it is entirely possible for farm households to benefit from adverse climate developments if the adverse shock is widespread, if farm level demand for their product is quite inelastic, if there are few sources of off-farm income, if food is a small share of expenditures, and if supply response is relatively low.[5]

In their survey, Adams et al. (1998, p. 28) emphasize the potential for agricultural producer gains from adverse climate shocks, noting that, while consumers are expected to lose from higher agricultural prices, producers are projected to gain, due to inelastic demand for their products. These authors also draw attention to the fact that the consequences of climate change for local and regional factor markets have been "largely unexplored, but are potentially important" (p. 29). Thus it is worth our while to explore these effects more carefully.

Factor markets and the impacts on nonfarm households

The key difference between farm and non-farm households is that the latter group's earnings are not directly affected by the adverse change in on-farm productivity, since, by definition, they do not receive farm income. The earnings of these non-farm households will only be affected indirectly, for example through a change in wage rates.[6] In cases where agriculture is a major employer in the economy—particularly for unskilled workers—it is possible that the earnings of poor, nonfarm households might be significantly affected through changes in market wages when there is a significant shock to agricultural productivity and/or prices.

Ravallion (1990) considers the welfare impact of an exogenous rise in the price of rice on the rural poor in Bangladesh. The analytical framework which he develops is quite instructive and sheds light on the likely indirect impacts of higher agricultural prices on rural non-farm households employed in farming as separate from the direct effect of climate change on labor demand. He decomposes the welfare impact into a spending effect, which simply depends on the household's net expenditure share on food grains, and an earnings effect. The earnings effect is the product of the household's income share from agricultural wages and the economy-wide wage-price elasticity. In the short run, Ravallion's estimates suggest that the impact of a food price increase will be negative, since the adverse spending effect dominates the favorable, but small, earnings effect. However, in the long run (about five years in this case), the wage-price elasticity (which increases with time) provides the potential for a rise in real income for these landless agricultural households in Bangladesh. So the time frame matters—particularly when considering indirect earnings effects.

In regions where climate change affects the local demand for labor as well as prices, the impact on wages is more complex. The competing effects at work are well illustrated in Banerjee (2007), who focuses on the impact of flooding on agricultural wages in Bangladeshi labor markets. Depending on the timing of the floods, this natural disaster can depress or

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[5] *A formal set of conditions for farm households to gain from an adverse climate shock is given in the appendix available from the authors.*

[6] *Of course there will also be households in the economy whose earnings are not affected—either directly or indirectly—by the climate change impacts in agriculture. For these households, the spending side effect is the only relevant one, so they will be unambiguously hurt by higher food prices following an adverse climate event.*

boost unskilled wages. For example, if the flood requires replanting of the fields, the demand for labor may rise as a consequence. On the other hand, massive flooding has a dampening effect on wages as the demand for labor is reduced. Overall, he finds that the impact of floods on agricultural wages in Bangladesh varies depending on the timing of the event, its severity, and the length of run considered.

The aggregate national poverty impact of an adverse climate change event will depend on the cumulative effect across all low income households in the economy. While we generally expect an adverse climate event to increase poverty, because of the spending effect which hits all households, the preceding analysis suggests that this is not a foregone conclusion. There are circumstances under which the national poverty head count could actually fall. Such an eventuality is most likely when the following four conditions hold jointly. First, the adverse climate change is not localized and farm level demand and supply are inelastic, so that agricultural prices and farm factor returns rise sharply, dominating the adverse spending effect for farm households. Second, poverty is concentrated in agriculture so that the majority of the poor are favorably affected due to the first condition. Third, the adverse climate shocks result in a sustained increase in labor demand. Lastly, if the farm sector represents a large share of the unskilled labor demand in the economy, the net result of all these conditions can give rise to significant indirect wage effects such that the non-farm poor might benefit from higher wages.

The poverty impacts of climate change, both direct and indirect effects, are complex and cannot be fully anticipated based on theoretical arguments and econometric studies alone. Thus, as with the issue of climate change attribution, a simulation model is required. Only this time, rather than a General Circulation Model of global climate, such studies rely on Computational General Equilibrium models of the global economy.

Hertel, Burke, and Lobell (2009) use the poverty-extended version of the Global Trade Analysis Project (GTAP) model to explore the impacts of adverse climate change on different segments of population living on $1/day across a sample of 15 developing countries. Under their adverse climate scenario for 2030 (an occurrence with only 5 percent probability), global staple grain prices rise by 10–60 percent, and agricultural returns rise sharply in most regions. Average poverty rates fall in the agricultural specialized households (95 percent or more of earnings from the family's farming enterprise), as well as the diversified households (also receiving significant farm earnings), while the average poverty headcount rises for rural and urban wage labor households, non-farm, self-employed and transfer payment dependent households. National poverty rates fall in about half the countries—these are nations in which poverty is concentrated in agriculture and overall climate productivity shocks are not as severe (e.g. Chile and Thailand). Countries in sub-Saharan Africa stand out as showing the most severe yield impacts from this adverse climate change scenario; none of the population groups in these countries experience significant poverty reductions and the national poverty headcount rises in all of the African countries in their sample.

Hertel, Burke, and Lobell also consider a "high productivity" scenario for 2030 (again just 5 percent probability of this occurring) in which world prices fall as a result of climate change. Here, the results are largely reversed, with poverty falling amongst urban and wage earning households, and rising amongst those households earning their living in farming. The authors' most likely climate change scenario for 2030 (the mean outcome from this uncertain distribution of climate shocks) suggests little change in world prices due to modest productivity effects and offsetting impacts in northern (higher yields) and tropical (lower yields) latitudes. Consequently the poverty impacts are muted.

However, as previously noted, gradual climate change may be less onerous for the poor than the occurrence of extreme climate events such as flooding, drought, and heat waves. The poor tend to be more vulnerable to extreme events since they live in more exposed locations, spend more of their income on food, and rely heavily on farming for their incomes. Ahmed, Diffenbaugh, and Hertel (2009) use the same basic modeling framework as Hertel, Burke, and Lobell (2009) to explore the impacts of extreme (1 in 30 chance) adverse climate events in the current (1970–2000) climate as well as in the future (2070–2100) climate. These authors find that current climate volatility has a particularly severe impact on poverty in Bangladesh, Southern Africa, and Mexico, with urban wage-earning households experiencing the sharpest increase in poverty. In attempting to predict the impact of increasingly intense extreme climate events in the future, the authors focus on the impact of drought (measured as the longest period of consecutive dry days) which increases in 11 of the 16 countries under examination. They find the largest rises in national poverty headcount in Zambia (4.6 percent of the national population) and Mexico (1.8 percent of the population) as a result of these increased climate extremes.

Impacts on non-priced goods

Climate change can also affect the poor through its impacts on the availability of non-priced goods and services from renewable natural resource endowments. Examples of natural resource goods which are relevant to household consumption, production, and asset accumulation include: wild foods, medicines, consumption/production goods (gum, soap, salt, resins, dyes, etc.), construction materials, energy sources, furnishings, tools and utensils, fertilizer, grazing and fodder, clay for pottery, timber, and mineral resources. "Two characteristics aside from their renewability make environmental resources different from other economic activities: their spontaneous occurrence, and the fact they are so often held under communal tenure" (Cavendish 2000, p. 1980) It is also common for these types of goods to be non-traded, even in local markets. For example, only 19 percent of surveyed villages bordering the Sariska Tiger Reserve in India had local markets for firewood even though it constitutes 59 percent of the total biomass energy consumed (Heltberg 2001; Heltberg, Arndt, and Sekhar 2000).

In aggregate, natural resources also provide services for soil conservation, water availability and quality, biodiversity conservation, carbon sequestration, and air quality (Duraiappah 1998). For example, wetlands can filter pollutants from water sources and improve the quality of irrigation and drinking water; forest cover on steep slopes can prevent erosion and loss of top soil for low-land fields; and natural habitats support pollinator and pest predator species which reduce the costs of inputs for cultivation (Kevan 1999; Sunderlin et al. 2005). These ecosystem services affect the quality of life for households as well as the profitability of agricultural technologies. To illustrate, increased erosion from deforestation may increase silt levels in irrigation water, thereby decreasing the efficiency of irrigation canals. Likewise, removal of mangroves and wetlands along coastal areas can increase saltwater incursions into groundwater sources, increasing salt levels in irrigation water and decreasing agricultural yields.

In many cases these ecosystem goods and services may be quite sensitive to climate change. Under most climate change scenarios, changes in rainfall and temperature are predicted to alter the mix of local plant species. Using 23 different climate change scenarios, Battisti and Naylor (2009) found a greater than 90 percent probability that, by 2100, the average summer temperatures in the tropics and subtropics will exceed the recorded high temperatures from 1900–2006. As average and maximum temperatures increase, the productivity and viability of plant species change, particularly above the threshold temperature of 35°C (Schlenker and Lobell 2009; Schlenker and Roberts 2006). Thus climate change is likely to cause species loss as well as altering the types of fauna supported by an ecosystem (McCarty 2001; Walther et al. 2002). Further, climate change is likely to introduce new pest and predator species and reduce beneficial species—factors which are particularly critical for agriculture (Kevan 1999).

Reductions in natural resource goods and services are likely to have a significant impact on the poor. Empirical evidence from household surveys in Zimbabwe estimate that poor households derive as much as 40 percent or more of their incomes from environmental goods (Cavendish 2000), and 24 percent of incomes in Peru (Takasaki, Barham, and Coomes 2004). An estimated 31 percent of household production income derives from bush meat in the Democratic Republic of Congo (de Merode, Homewood, and Cowlishaw 2004) and 75 percent of surveyed households in Brazil devoted time to collecting non-timber forest products (Pattanayak and Sills 2001). Natural resource goods also represent a significant fraction of cash incomes (Cavendish 2000; de Merode, Homewood, and Cowlishaw 2004). De Merode, Homewood, and Cowlishaw found that, in Congo, 90 percent of bush meat and fish caught, as well as 25 percent of harvested wild plants, were sold in urban markets. On the whole, the contribution to poor incomes from environmental goods can approach the levels of income from cash crop production, unskilled labor wages, and small businesses and crafts (Cavendish 2000).

Many factors come into play in determining how much households rely on environmental goods. Proximity to accessible resources is important (Heltberg, Arndt, and Sekhar 2000; Pattanayak and Sills 2001; Takasaki, Barham, and Coomes 2004). Households that receive remittance incomes (Eriksen, Brown, and Kelly 2005; Cavendish 2000) or have children living away from the village (Pattanayak and Sills 2001) tend to devote less time to collecting natural resource goods. In their research on Malawi, Fisher and Shively (2005) noted that younger and male-headed households relied more heavily on environmental resources. Cavendish saw similar findings for households headed by divorced and widowed men in Zimbabwe. He hypothesized that male-headed households relied more heavily on environmental goods for cash income in order to hire women for female-specialized tasks. Heltberg, Arndt, and Sekhar (2000) noted that lower caste villagers in India spent more time on firewood collection and consumed more firewood than higher caste households. Cavendish (2000,

p. 1990) concludes: "Lower income households clearly depend proportionately more on the consumption of wild foods than do higher income households, evidence perhaps that these households are unable to allocate as high a share of cash income to purchased foods as better-off households."

Natural resource goods often have limited substitutes, further complicating the adjustment of households to potential reductions in the availability of these goods in the wake of climate change. Analyzing eight developing countries, Heltberg (2004) found that higher incomes are associated with greater adoption of modern fuels, but that households in many countries preferred to use multiple fuel sources including biomass. He also found that households in Ghana and Nepal showed very little tendency to switch away from biomass energy in the wake of relative price changes.

To summarize, the link between natural resources and poverty is complex and highly contingent on local endowments and cultural norms. Climate change is expected to alter the goods and services that natural resources can provide in developing countries, which will disproportionately affect consumption, production, and asset accumulation of the rural poor.

Dynamics of Adaptation

With the framework in place connecting the impacts of climate change to agricultural production and then to poverty, we return to the question of adaptation. As previously discussed, the impact of climate change on poverty depends critically on the time frame over which it occurs. Households are better able to adapt to gradual changes; short run climate shocks do not allow sufficient time for adaptation, generally speaking.

Adaptation is an inherently dynamic process and occurs in the context of other endogenous dynamic processes including population growth, migration, technological change, economic growth, and structural transformation. Adaptation can take place at different decision-making scales (household, organization, national) and at different geographical scales (Risbey et al. 1999). It can be shaped by environmental factors such as proximity to town/market, proximity to year-round water sources, and adequate precipitation for agriculture and livestock (Ziervogel, Bharwani, and Downing 2006, p. 295). Adaptation decisions are also shaped by the policy environment in which decision-makers operate, i.e. social safety nets, trade policies, market price support and stockholding, land tenure and water rights, and the ability of stakeholders to participate in political processes (Adger et al. 2007; Kelly and Adger 2000; Smit et al. 2001; Smit and Wandel 2006). The net result of these complicating factors makes it challenging to observe adaptation empirically and to forecast the potential for such adaptation to mitigate adverse impacts from future climate change. However, the historical record of adaptation to climate events can give us some bounds on expectations.

Several recent and comprehensive surveys of the adaptation literature exist, including the second working group's contribution to the IPCC report *Climate Change 2007* (Adger et al. 2007), Smit and Wandel's (2006) review of adaptation and vulnerability, Adger's (2003) synthesis of the literature on social capital and adaption, Agrawal's (2008) report on institutional adaptation, and the work by Raleigh, Jordan, and Salehyan (2008) on migration and conflict induced by climate change. For this article, we focus solely on climate change adaptation strategies which bear on agriculture and natural resources, examining their potential impacts on rural household wealth and economic growth. This allows us to tease out the factors that constrain these adaptation strategies and the potential for policy to address these constraints.

Climate risk and on-farm decision-making

Climate risks are an important determinant of fluctuations in farm household income. Dercon (2006) found that drought was the predominant source of serious shocks leading to loss of assets, income, and consumption for rural households in Ethiopia. Sampled households which experienced drought in the last two years showed an average consumption reduction of 16 percent relative to households which did not experience drought; households which experienced a drought two years before that still showed a 14 percent consumption reduction; and the overall poverty headcount in the sample would have been one-third lower in the absence of drought. Even modest climate events can have sharp effects on rural incomes. A delay in the onset of the monsoons in rural villages in India by just one standard deviation can reduce agricultural profits for the poorest households by more than one-third (Rosenzweig and Binswanger 1993).

It takes farm households ten years, on average, to rebuild livestock holdings in the wake of drought (Dercon 2006). Given this slow response, it is important whether the adverse climate shock occurs only once every 30 years—thereby allowing time for recovery—or whether it is repeated in two (or more) successive years. This is a particular concern in light of the evidence cited above of the likelihood of increased frequency and intensity of extreme climate events in the future. Successive droughts can have a devastating impact on low income households from which it will be hard to recover—even in the long run.

Farm households adopt a variety of risk minimization techniques—such as planting a variety of cultivars, planting multiple crops, or staggering planting dates—in order to diversify against climate risks. However, these strategies can result in reduced long run expected profits. Farmers in Andhra Pradesh who plant a mix of crops that hedge climate risks saw reduced variability of agricultural revenue but also saw lower average incomes (Gine, Townsend, and Vickery 2007). In a study of resettled households in Zimbabwe, Elbers, Gunning, and Kinsey (2007) found that households that face both idiosyncratic (household-specific) risks as well as covariate (region-wide) risk from erratic annual rainfall saw a 46 percent reduction in long run expected capital stock. In this particular case, which is somewhat peculiar due to various restrictions placed on the households in the resettlement scheme, they found that the *expectations of such shocks* (ex ante risk) was more damaging than the *climate shocks* (ex post risk), accounting for two-thirds of the risk-induced reduction in asset accumulation. In other words, it is not the adverse shocks themselves, but rather the expectation of these extreme events which curtailed growth and the accumulation of assets (measured in livestock units).

The choice strategy pursued by rural households to minimize climate risk depends on household wealth (Gine, Townsend, and Vickery 2008; Lybbert et al. 2004; Rosenzweig and Binswanger 1993; Ziervogel, Bharwani, and Downing 2006). In a case study of South African farmers, Ziervogel, Bharwani, and Downing found that wealthier households made planting decisions that were less diversified for climate risks than poor ones in order better to target market demand and maximize profits: "Better-off entrepreneurial farmers tend to block plant their whole plot with a single market crop, thereby producing a good income in a good year or potentially significant losses in a bad year." The different climate risk strategies pursued by wealthier households can result in profoundly different average profit outcomes. Rosenzweig and Binswanger found that increasing the coefficient of variation of rainfall by one standard deviation reduced estimated farm profits for the poorest wealth quartile by 35 percent, while the richest quartile was virtually unaffected by more uncertain rainfall.

A similar division exists for wealthy and poor cattle herders in Ethiopia. Lybbert et al. (2004) found a threshold level of cattle ownership above which pastoralists can engage in more "opportunistic, spatially flexible herding" strategies and realize lower herd mortality rates. Households below this threshold have less flexibility given adverse climate shocks and draw more intensively on the remaining herd for nutrition, thereby boosting herd mortality rates and resulting in smaller equilibrium herd sizes. Poorer pastoralists with smaller herds must supplant their food supplies with purchased, harvested, or donated food, constraining their ability to migrate to better grazing lands. Their ability to maintain depleted herds is further eroded by policy efforts to establish clear land tenure and push for permanent settlement of these pastoralists, undermining the traditional resiliency of herding against climate variability.

Impact of policy for on-farm decision-making

Because sensitivity to climate risks decreases with increasing wealth, policies to reduce the effective level of climate risk, such as investing in more accurate climate forecasts and/or providing insurance to allow for smoothing of consumption and investment, should be particularly beneficial for poor farmers. Empirical studies, however, offer conflicting assessments of the potential for either policy to impact on the decision-making process of the poor.

Gine, Townsend, and Vickery (2007) found that farmers in India with fewer risk-coping mechanisms invested more effort in acquiring accurate weather prediction information. This was because:

> farmers who believe the monsoon will start later are also more likely to plant later. Likewise, they are less likely to replant, have purchased a lower share of total production inputs before the onset of the monsoon and are more likely to buy weather insurance, since according to their beliefs, the probability of a payout is higher. All of these findings provide strong evidence that individuals make decisions according to their prior expectations, even when controlling for self-reported proxies of risk aversion, discount rates and the actual start of the monsoon. (p. 5)

Other studies, however, have concluded that farmers give relatively little weight to climate forecasts when making planting decisions due to poor spatial and temporal resolution, and lack of trust for the institution issuing the forecast. In a case study of 200 farmers in Argentina, Letson et al. (2001) found that farmers rely on price expectations (33 percent), crop rotation patterns (22 percent), and climate projections (16 percent) in making planting decisions. Older farmers relied less on climate projections, but experience of farming during the 1997–98 El Niño event shifted farmers toward a greater confidence in climate projections. This suggests that farmers may increase their demand for accurate climate forecasts as climate change renders their traditional information sources and experience less reliable.

Herders in southern Ethiopia and northern Kenya also made little use of modern forecasts, even when they had confidence in the forecast, because of the inherent flexibility of herding and an abundance of grazing lands (Luseno et al. 2003). Those herders who did rely on forecasts preferred to use traditional methods, e.g. animal intestines, clouds, birds, etc., over modern forecasts. Herders had confidence in these methods because they were spatially detailed, transmitted in local languages by trusted local experts, and focused on the onset of the rains rather than total precipitation.

Increasing the usefulness of modern climate forecasts depends on "developing focused knowledge about which forecast information is potentially useful for which recipients, about how these recipients process the information, and about the characteristics of effective- information delivery systems and messages for meeting the needs of particular types of recipients" (Stern and Easterling 1999, p. 94). The majority of herders studied by Luseno et al. had no access to modern forecasts transmitted through radio and newspapers. This suggests an opportunity for an extension of services from agricultural ministries, NGOs, or donor agencies to work with local farmer groups to develop and deliver effective forecasts targeted at the poorest groups.

Insurance is the canonical solution for managing risks such as changing climate conditions. Yet poor people rarely include insurance as one of their strategies for diversifying risks. This lack of insurance can be partially explained by undeveloped insurance markets in many rural areas. Even when insurance markets exist, however, the poor do not always choose to purchase insurance (Kiviat 2009).

Dercon found that, due to the covariate nature of shocks from droughts, households were unable to insure against them using traditional risk sharing mechanisms such as local credit, asset markets, transfers from local households, and networks. Unlike idiosyncratic shocks, such as illness or accidental death, which can be insured through informal networks of families in the community or through the sale of livestock, droughts affect the entire community and depress the prices for livestock, as all families are pressed to maintain consumption levels.

Improving insurance against climate risks, in addition to helping households smooth consumption after climate shocks, also has the potential to increase child schooling and thereby their lifetime expected earnings (Jacoby and Skoufias 1997). In a study of 10 villages in India, unanticipated income shocks affected child school attendance; idiosyncratic risk had the smallest impact on school attendance in those villages with the most consistent rainfall and most developed financial markets. When incomes declined, and local financial markets were incomplete, families withdrew children from school in order to add to household labor income or participate in home production. Credit market constraints between villages affected schooling decisions for both large and small households, although only smallholders tended to be inadequately insured on an exante basis.

One method of increasing insurance coverage for the poor is to provide public weather index insurance (also referred to as parametric insurance).

Index insurance pays out when certain trigger events occur, such as rainfall levels measured by local rain gauges fail to meet an established threshold. Weather insurance is often provided as a public good because the risks from weather events are highly correlated across households. Further, publicly provided insurance has low transactions costs, can be more transparent than private insurance, has low administrative burdens, can provide rapid payouts, and minimizes asymmetric information problems (Gine, Townsend, and Vickery 2008). Pilot programs are currently underway in Mexico, Peru, Nicaragua, Honduras, and Guatemala to introduce index insurance into existing insurance markets (Arce 2008).

Few studies exist yet of the adoption of index insurance by poor farmers. In one such study, farmers in Andhra Pradesh who devoted a large share of their cultivation to castor and groundnuts—both highly profitable and highly sensitive to drought—were more likely to purchase rainfall insurance from a microfinance institution (Gine, Townsend, and Vickery 2008). Wealthier households were also more likely to purchase weather insurance as credit constraints were a significant barrier for the poor. Reputation of the microfinance institution played a large role in household decisions to purchase insurance; insurance purchases increased with household familiarity with the microfinance institution and with increasing participation from other members of the household's social networks.

Gine, Townsend, and Vickery (2008) offer criteria for a well-designed index insurance mechanism. Firstly, it should be transparent and verifiable to policyholders. It should be based on a measure which can be determined cheaply and quickly, whose calculation is not vulnerable to tampering or manipulation, and whose ex-post measures are highly correlated with household incomes and consumption risks. Index insurance also requires an underlying probability distribution which can be estimated with some accuracy. Such distributions, however, are likely to be highly sensitive to climate change. Finally, they note the importance of offering credit for the poorest households seeking such insurance, as the timing of the premium payments can present a real obstacle to the purchase of insurance by the poor.

Although there is not yet enough evidence to draw definitive policy prescriptions, the potential exists for index-based insurance to compensate for covariate climate shocks. This may give impetus for poor farmers to adopt less diversified but more profitable crop choices, provided the insurance payments are administered by a trusted, credible party. However, shifting the agricultural sector toward less climate risk diversification increases the national burden on public and private insurers. Even with the wealth, capacity, and developed insurance markets in the United States, private insurers have been less able to cope with extreme weather risks and government programs have reduced their coverage levels (Mills 2005). Thus the net poverty benefits of establishing index-based insurance in any developing country must be carefully weighed against potential future public liabilities.

In addition to index insurance and more effective climate forecasting, policies which improve development in general—investing in human capital and infrastructure, facilitating seasonal and permanent migration—also have potential to support the rural poor in adapting to climate change. Investment in water storage and irrigation is particularly import for rural incomes. Changes in the pattern and timing of precipitation under future climate scenarios have the potential to disrupt seriously water availability around the world (Molle and Mollinga 2003). Case studies in Asia and the Middle East have shown that farmers react to water scarcity by challenging the water allocation environment, including tampering with infrastructure, colluding with water officials, organizing protests, and lobbying political connections (Molle et al. 2009). Water scarcity can be countered by a range of policy options, from low capital techniques, such as promoting strategic fallowing and shifting planting calendars in order to capitalize on residual soil moisture, to high capital techniques aimed at augmenting water supplies. Institutional changes have also been observed to improve conservation efficiency and equity of water allocation, including setting up rotation irrigation, creating water user associations to negotiate during times of water scarcity, collective pumping operations, and policies to improve river-basin management (Molle et al. 2009). Given the wide range of costs and technological capacity required for the various policy alternatives, dialogues between stakeholders may be helpful in identifying the combination of policies with the most potential at the local level to address water scarcity for the rural poor.

Adaptation and economic growth

Over longer time periods, the cumulative impact of climate change and associated adaptation can alter the path of economic growth and poverty. Thurlow, Zhu, and Diao (2008) estimate that the impact of climate variability on crop yields over the past three decades has reduced the rate of GDP growth in Zambia by 0.4 percentage points per year. This translates into a US$4.3 billion loss over a 10-year period, and is estimated to keep an additional 300,000 individuals below the poverty line by 2016. "While most of these people live in rural areas, climate variability also greatly increases urban poverty due to higher food prices and lower real urban incomes … Indeed, the national poverty rate may rise by as much as eight percentage points in particularly severe drought years" (Thurlow, Zhu, and Diao 2008, pp. 48–9).

Three case studies of historical adaptation to climate and population stresses described by Kates (2000) offer a pessimistic view of the potential for the interplay of adaptation and economic growth. Although adaptations to nearly 30 years of drought conditions in the Sahel have led to many positive policy innovations such as improved early warning networks, better coordinated and funded food aid programs, increased crisis planning and reaction capabilities by local governments, and improved transportation and marketing services for agriculture, they have not translated into economic growth or reduced poverty levels. "Thus, over time, there is an improving capability to respond to drought as an extreme event, to prevent famine, and to save lives. There is little success however in adjusting livelihood systems to the persistent drought and the stress placed on the ecological systems supporting agriculture and pastoralism" (Kates 2000, p. 10).

Several historical case studies discussed by Fraser (2007) offer a pessimistic view of adaptation to climate change. He examined adaptation during the Irish potato famine, El Niño-induced droughts in the Philippines and Indonesia in the 1870s, and the Ethiopian famines of the

20th century. All three instances were characterized by high rural population densities, specialized crop production (as opposed to a diversity of crop species), and a few non-farm income-generating alternatives. These three factors, combined with institutional responses, tended to exacerbate the crises.

The second case study also highlights the perverse consequences of trade (both international and intra-national) during a crisis: "when the droughts struck, instead of allowing food to be imported, rail and telegraph networks meant that locals were competing with much wealthier consumers from elsewhere" (Fraser 2007, p. 8). The latter finding contrasts sharply with the results of Donaldson (2008) who estimates the impact of railroad access on the volatility of local food prices and real incomes in 19th-century India. He finds that, when railroads were extended to new rural districts in India, real agricultural incomes in that district rose by 18 percent, while commodity price volatility and real income volatility were reduced.

What overarching conclusions can we draw from this body of empirical research on adaptation and rural poverty? Farm households' strategic decisions are influenced by many factors including risk aversion, wealth levels, climate variability, and the surrounding policy and institutional environment. They may make use of adaptation strategies such as insurance, migration, technological change, investment in human capital, and reliance on natural resources, depending on how these strategies are supported by institutions and policy environments. In many areas today, farmers prefer to rely on traditional knowledge and methods of forecasting climate for their planting decisions, although this may not persist as climate signals become noisier. As noted by Quiggin and Horowitz:

> Another way of looking at this is that the information held by economic actors about the climate becomes more diffuse, and hence less valuable in the presence of a new source of uncertainty. Thus climate change may be regarded as destroying information. This information may in some cases be represented by formal probability distributions over temperature and rainfall derived from historical records. More frequently, it is the informal knowledge of particular local climates that is acquired by attentive individuals over a long period. (2003, p. 444)

Access to credit, assets, social networks, and safety nets all shape the decision environment, and the opportunity to migrate (if only seasonally) provides a crucial coping mechanism when local capacity is overwhelmed by disasters. Yet "the same resource—whether cattle, land, or education—will not be equally important for adaptation in all contexts" (Eakin 2005, p. 1934). Policy choices which can improve livelihoods today—such as improving insurance markets, investing in relevant climate forecasting capabilities, establishing water management institutions, and facilitating migration—also have the potential to aid farmers in adapting to climate change but may not raise the general population above a new subsistence equilibrium. Lastly, the poverty impacts of climate events can be severe and may persist for generations.

Climate Change Mitigation and Poverty

Thus far we have focused our attention on the poverty impacts of climate change, potential adaptation strategies which the poor may adopt, and the ways in which the policy environment shapes the adaptation process. However, as the global community focuses increased attention on climate change mitigation, the potential for such mitigation efforts to have an impact on poverty increases. We argue here that the poverty consequences of policies to mitigate climate change could potentially rival in importance the poverty impacts of the climate change itself.

Forestry and agriculture account for roughly one-third of global GHG emissions (IPCC, figure 2.1) thus offering tremendous potential to contribute to climate change mitigation programs. Furthermore, at a carbon price of $100 per ton CO_2 equivalent, the combined mitigation potential of agriculture and forestry is greater than that of any other individual sector in the economy (WDR, p. 25). Golub et al. (2009) estimate that, in the next two decades, these sectors could account for as much global abatement as would be attained from reduced fossil fuel consumption based on a global carbon tax of $28 per ton CO_2 equivalent.

Much of this low cost abatement is due to avoided deforestation in the tropics. This has focused considerable international attention on programs for reducing emissions from deforestation and degradation (REDD). Indeed, a handful of wealthy nations committed a $3.5 billion down payment for REDD—with much more to follow—at the recent climate summit in Copenhagen (*The Economist*, December 17, 2009). As it happens, much deforestation occurs in areas with relatively high poverty rates—namely at the frontier in developing countries. This opens the possibility of significant interactions between climate change mitigation efforts and poverty.

There are two channels through which mitigation policies can affect poverty. The first of these is through payments for environmental services. When the poor are involved in efforts to sequester carbon, the payments to these households may directly serve to alleviate poverty. One such project is currently underway in the 1.2 million acre Juma Sustainable Development Reserve of the Brazilian Amazon. In this Reserve, carbon offset funds from wealthy countries have been made available and are used to pay local households to protect the forest. Each family gets about $28 per month placed on a debit card, provided regular inspections show that deforestation is not progressing. Additional offset funds are used to support investments in schools, hospitals, and local infrastructure (*The Economist*, September 24, 2009). While such projects appear to have great appeal, only time will tell if they are up to the task of preventing deforestation of the Amazon in the face of very significant outside economic pressures, and if they can be scaled up fast enough to match the global mitigation agenda.

REDD is a relatively new initiative. The Kyoto Protocol, which has governed international mitigation since its signing in 1997, did not target avoided deforestation. Instead, it offered incentives for reforestation in developing countries under the Clean Development Mechanism (CDM). Gong, Bull, and Baylis (2010) offer a comprehensive review of the success of the very first CDM project undertaken in the Guangxi Province of China. It bundled 4,000 hectares of degraded lands, assembled from 27 separate villages in order to attain the scale economies necessary to attract investors. Local households were assigned shares in this project and three local forest products companies were involved in the enterprise. Indeed, sales of timber and pine resin were expected to generate more revenue overall than the carbon credits. The credits amounted to an estimated $4.5 per ton CO_2 equivalent and were provided by the World Bank BioCarbon Fund.

Gong, Bull, and Baylis (2010) find some evidence of success in this project. Of the targeted area 55 percent has been reforested and payments have been flowing to the local households. They find that even in the absence of clearly defined property rights in this region, strong social capital was able to facilitate success. However, they predict that the reforestation will not go much beyond this level due to (a) the high costs of reforestation on the more remote, highly degraded land, and (b) insufficient contract flexibility to differentiate effort by land type and location. The authors do not explicitly address the poverty impacts of the project, but clearly the pooling approach offers an important opportunity for small scale, low income households to participate, with potentially favorable impacts on poverty rates.

Pagiola, Arcenas, and Platais (2005) focus on the poverty impacts of payments for environmental services (PES) in Latin America—of which carbon offsets are one example. They conclude: "PES programs are not a magic bullet for poverty reduction, but there can be important synergies when program design is well thought out and local conditions are favorable" (p. 248). Because such payments are tied to land, their distributional impacts are inherently tied to the distribution of land ownership in the target region. Since rural land ownership is highly correlated with income, this immediately biases the programs toward the wealthier households. Also, transactions costs for the program (e.g. contracting costs, management plans) are largely independent of farm size and therefore most onerous for small farms. These fixed costs also create an incentive for those administering the program to work with larger entities—a classic adverse selection problem that reduces the poverty-reduction potential of PES. Pooling land—as in the case of the Guangxi CDM project discussed above—or for working with local collectives raises the net payoffs for all participants, including poor households.

In the frontier areas where deforestation is most active, land tenure is often insecure. When coupled with credit constraints, this makes it very difficult for low income households to participate in such programs. On the other hand, by minimizing transactions costs, front-loading payments, and working to ensure title to the land, it is possible to increase the participation of the poor in such programs. Yet in the end, Pagiola, Arcenas, and Platais offer some sobering evidence on the potential for PES to reduce poverty. They point out that *even those programs which are explicitly designed to reduce poverty* in developing countries have limited success. Citing Coady, Grosh, and Hoddinott (2004), they note that the median targeting rate for poverty reduction programs across a large sample of countries is only 1.33 (i.e. the median program transfers only 33 percent more income to the bottom decline than would a uniform transfer program to all households in the economy). Any program with the primary objective of reducing carbon emissions cannot hope to do much better than this, and will likely do worse.

The second channel by which mitigation policies impact poverty is through indirect impacts on commodity and factor markets (in much the same way as the climate change impacts discussed above). This potential for indirect effects is illustrated by the contribution of biofuels programs—motivated themselves in part by GHG mitigation objectives—to the recent run-up of world food prices. Mitchell (2008, p. 17) attributes as much as three-quarters of the rise in food commodity prices over the 2002–08 period to biofuels and the related consequences of low grain stocks, speculative activity, and export bans. Others suggest that the contribution of biofuels to this price spike was much more modest. However, any program which contributes to the majority of global growth in cereals demand, as did the U.S. ethanol program over the 2005/6–2007/8 period, must be viewed as a significant development (Westhoff 2010, pp. 14 –15).

The poverty impacts of higher commodity prices induced by mitigation efforts are unclear for the same reasons identified earlier—namely higher prices have the potential to benefit rural agricultural households where many of the world's poor reside. In an attempt to resolve this ambiguity, Hertel and Taheripour (2009) analyze the impact of combined EU and U.S. biofuel mandates on world markets and on poverty in a sample of 18 developing countries. Their results show that these policies consistently reduce poverty headcount rates for agriculture specialized households, while boosting them for both wage labor and non-agricultural, self-employed households. National poverty headcount changes depend on the composition of poverty; Asian countries show poverty reductions due to the predominance of rural poverty in those sample countries; while poverty rises in most of the Latin American countries is due to the urban concentration of poverty on that continent. Impacts on countries in Africa were limited due to their modest integration in world markets. De Hoyos and Medvedev (2009) estimate the impact of the growth in biofuel production from 2004–10 and find that it boosts the global poverty headcount by about 30 million people—mostly in South Asia.

The recent push for biofuels has, to date, been heavily concentrated in the United States and the EU, which has limited the global price impacts. However, a major, global initiative to reduce GHG emissions from agriculture and forestry—with much of the spending in the tropics—could have even more significant commodity price impacts in agriculture. The reason is that most of the abatement strategies serve to increase the global demand for land. Carbon forest sequestration is most obvious in this regard, but policies to reduce nitrogen fertilizer applications (an important source of nitrous oxide emissions), to sequester agricultural soil carbon, and to reduce methane emissions from paddy rice production and/or livestock all have the potential to require more land for a given amount of agricultural output. This in turn can have important impacts on commodity prices. For example, Golub et al. estimate that a global agricultural carbon tax/forest sequestration subsidy of $28 per ton CO_2 equivalent could boost world average prices by 31 percent for rice, 28 percent for ruminants, and 11–13 percent for other crops. In the context of the proposed U.S. climate change legislation (the so-called Waxman-Markey bill), McCarl (2009) estimates that mitigation efforts could result in the diversion of nearly 50 million acres from cropland to forest cover in the United States, causing corn prices to be twice as high as they would otherwise be in 2050.

In summary, the linkages between climate change, agriculture, and poverty are not merely restricted to climate change impacts affecting agriculture and hence poverty. Many of the policies aimed at mitigating climate change have the potential to affect the poor, either directly through payments for environmental services rendered by low income households, or indirectly through commodity and factor markets. And, as shown here, there is potential for these effects to be quite significant; they should not be overlooked.

Synthesis and Policy Implications

A great deal has been written about climate change in the past two decades. Poverty has also received increased attention, especially in the context of the Millennium Development Goals. However, the link between climate change and poverty has been far less thoroughly examined. Understanding this link is vital for the formulation of intelligent, effective policy responses to climate change. In this article, we have focused on agriculture as the primary means by which the impacts of climate change are transmitted to the poor, and as a sector at the forefront of climate change mitigation efforts in developing countries. In so doing, we have been able to offer some important insights that may help shape future policies as well as ongoing research in this area.

A first point is the key role of potential earnings effects precipitated by market responses to climate change. To date, most studies have focused solely on food availability and prices, yet higher food prices in the wake of adverse climate change can also translate into higher incomes for producers. In some regions, this could lead to poverty reductions, particularly in those areas (i) which are less severely affected by climate change, (ii) where poverty is concentrated in rural, agricultural areas, and (iii) where adverse climate shocks boost the demand for unskilled labor (e.g. through the need to replant fields). A further complication arises due to the prevalence of non-priced goods in the consumption and earnings bundles of poor households. Adverse climate impacts on publicly accessible forests and wildlife resources could have a significant adverse impact on the poor who rely on them for firewood, food, and other consumption items. In short, the poverty consequences of climate change are much more nuanced than has been suggested in most discussions to date. It is not simply a question of how food price impacts on low income consumers.

With the proliferation of studies assessing the likely agricultural productivity impacts of climate change, policymakers are in desperate need of guidance regarding the comparability and reliability of such reports. We have evaluated the three main approaches to assessing these impacts and conclude that each has its own limitations and should not be used in isolation. Decision makers must press those doing crop simulation analysis for more regional and national scale validation of their work, while the statistical studies (including the Ricardian) analyses need to be carefully evaluated for robustness. In general, too little attention has been paid to the potential for climate variables exceeding key thresholds which might give rise to sharp drops in the productivity for some cropping activities.

While the effects of adverse climate shocks on the poor have received relatively more attention in the literature, it is entirely possible that the poverty impacts of attempts to mitigate climate change could have a much greater effect on the poor in some developing countries. Here, preliminary evidence suggests that both the direct effects of payments to sequester carbon, as well as the indirect effects of mitigation activities on wages and food prices, could have important poverty impacts. Of course, realizing potential poverty benefits of mitigation programs depends on both the extent that agriculture and forestry offer low cost mitigation opportunities and the extent to which governments are able to mobilize effectively resources to slow the rate of GHG emissions.

Because there has only been modest progress to date for mitigation efforts, policymakers should also consider ways to support the poor in adapting to climate change. As pointed out by Adger (2003, p. 388), adaptation is not a new phenomenon: "It is clear that individuals and societies have adapted to climate change over the course of human history and will continue to do so." We can learn a great deal from examining studies of the poverty impacts of historical climate events, which highlight these events as one of the most important reasons for households falling into or remaining trapped in poverty in rural areas. Because these events hit the entire population at once, traditional methods of risk sharing which work well for idiosyncratic events are no longer adequate. As a consequence, poor farming households are prone to modifying behavior in anticipation of such shocks, and these ex ante behavioral changes can cost them quite a bit in terms of future earnings.

Economists' traditional response to this problem is to offer weather insurance, and we now have a number of valuable studies which look at this potential solution. What is most surprising is the modest uptake of such insurance. Poor households are often distrustful of such schemes. They are also hard pressed to front the costs of even modest premiums, and, when disaster hits, they cannot afford to wait for the resulting payment. Much can be done to improve the value of weather insurance schemes to low income households. However, these schemes also carry with them the potential to increase aggregate risk by encouraging excessive crop specialization.

In the end, policymakers concerned about the impact of climate change on agriculture and poverty cannot wait for the academic community to resolve all the uncertainty that presently exists. As noted at the outset of this article, climate change is a "wicked problem," and wicked problems do not have clear-cut solutions. There is little to be gained by waiting another year or two before taking concrete steps to deal with this issue—particularly in countries where extreme climate events are already imposing severe burdens on the poor. Fortunately, many of the policies that are good for economic development in general also offer effective strategies for lessening the impact of climate change on the poor. Such strategies include improvements in (i) governance of common-pool natural resources, (ii) transportation and communication infrastructure as well as international trade facilitation to lessen the price impacts of regional climate shocks, (iii) irrigation and/or improved water management to deal with extreme precipitation events, (iv) credit and insurance markets, (v) investment in adaptive agricultural research, (vi) human capital to increase alternative employment opportunities of the poor, and (vii) facilitation of migration to allow poor households to take full advantage of changes in the economic landscape. These measures all serve to promote economic development while increasing the resilience of low income households to adverse climate events.

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