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CHAPTER

The farmer's climate change adaptation challenge in least developed countries*

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1 INTRODUCTION

The economics literature investigating climate change can be divided into two main themes. First, there is research on the mitigation challenge. This branch of the literature examines the costs of reducing greenhouse gas emissions from power generation, transportation and other key sectors. It also examines the economic incidence of reducing greenhouse gas emissions and studies the role of both the private and public sector in achieving this goal (Stern, 2008).

Rising global greenhouse gas concentrations portend that most nations will face increasing risks caused by climate change. Climate adaptation research investigates the economic consequences that are likely to unfold as human and natural systems respond to changing environmental conditions due to the evolving aggregate stock of greenhouse gas emissions. Vulnerability to climate change varies by geography and by the economic circumstances of the exposed population. Coastal areas will face the challenge of sea level rise, and most parts of the earth will face more extreme heat as well as increased temperature and rainfall variation. The further down in the within and across country income distributions households are located, the lower is the ability to adapt to these challenges as adaptive capacity is closely linked to income.

In the poorest nations, most people continue to work in agriculture. Given that these individuals work in maybe the most climate sensitive sector and have access to fewer costly adaptation strategies, it is essential to survey what we know and do not know about this vulnerable group's capacity to cope with this new climate reality.

In this survey, we present a micro economic approach for explaining adaptation choices and predicting challenges for poor farmers in the developing world. Building on the climate science that delivers predictions of shifts in the spatial distribution of temperature and rainfall patterns as well as natural disaster risks, we examine how farmers are expected to cope with the marginal increase in anticipated and in some cases unanticipated risks. Farmers have always faced climate variability. However, uncertain climate change adds to the volatility and persistence of this risk. Given the known unknowns about climate change, these risks are ambiguous in the sense that it is difficult to form precise expectations of future states of the world.

The poor have the least financial resources to cope with changing circumstances. The poor have been shown to have lower levels of literacy and less accumulated human capital. Such individuals would face constraints and challenges even in the absence of climate change. Climate change represents an additional challenge that manifests itself through changing poor peoples' production possibilities and the prices of goods they buy in markets as well as their access to natural resources such as water and animal feed that they need to achieve their daily goals.

We begin our survey in the countryside of the past, where farmers enjoyed a stable climate. We outline the basic decision problem a farmer faces and then introduce a shift in local and global climate. Given that a significant share of people in poor nations are farmers, we study how the well-being of farmers is affected by a set of climate change induced risks. An expansive literature in development economics has characterized the source of the climate risk and variability that farmers face in earning a living – the income variability due to weather shocks (Rosenzweig and Binswanger, 1993; Townsend, 1994). A more recent literature focuses on extreme events (Hsiang, 2010).

Climate change accentuates these risks in ambiguous ways. There is some uncertainty about how the spatial and temporal distribution of climate outcomes will evolve over the 21st century. The literature suggests that climate change will affect agricultural yields, health, energy production and consumption, water use, the spread of vector borne disease, labor productivity and incomes to name but a few. In this chapter, we study the causal chain, which begins with understanding the climate change induced risks to agriculture, with a special focus on the changing risks to subsistence farmers and their responses to this warm new world.

This survey delves into the econometric research designs that researchers have used to study "climate economics" (Carleton and Hsiang, 2016). Since researchers are unable to run field experiments in this setting, we pay close attention to the role of natural experiments and other instrumental variables strategies for recovering causal effects. We relate the statistical estimates to the economic objects of interest that are required for judging the economic incidence of climate change.

Urbanization represents one adaptation strategy. When young people move to the city, they often find employment in the service or manufacturing sector and this offers their rural family a source of diversified income. If enough rural residents move to the cities, this induces general equilibrium effects such that real per capita incomes increase in the countryside as rural wages rise and remittances received from the city increase. This sectoral integration between the rural and urban areas opens up potential topics for future research.

Urbanization and rising educational attainment are strong complements. Given that urbanization raises household income, urbanites have better access to electricity, housing, higher quality medical care, and market goods to protect themselves from climate change related challenges. While urbanization offers private benefits to recent migrants, as they would not have urbanized otherwise, such mass urbanization imposes both pecuniary externalities and social costs as the influx of migrants raises rents, lowers wages, and increases local public bads such as local air and water pollution. In the developing world, local governments may have limited fiscal capacity and incentives to manage these costs of city size. Our survey explores these issues.

To organize this survey, we will start with farmers in the country side who are exposed to a range of shifting shocks posed by climate change.

2 HISTORICAL AND ANTICIPATED CLIMATE CHANGE

There is overwhelming evidence that the observed climate has already shifted over the past 50 years and that this change is largely due to anthropogenic activities (IPCC, 2013). The Intergovernmental Panel on Climate Change (IPCC) has produced five assessment reports, which *synthesize* the state of the published climate science (the sixth report is currently getting started). The IPCC both studies observed changes in climate, by analyzing the historical record of temperatures across the globe as far back as data exist. For the very long past this done by looking at paleoclimate reconstructions using proxies, such as tree rings. For the more recent record, measured temperatures are analyzed. The IPCC concludes that over the period 1880–2012, the average land sea temperature has increased by 0.85 [0.65–1.06] degrees Celsius (IPCC, 2013). The observed changes are not uniform across space and season (IPCC, 2013, figure SPM1). Brazil, parts of the US and large swaths of Central Asia have experienced measurably larger increases in surface temperatures.

While detection of historical changes is challenging due to data availability and phenomena like the urban heat island effect, attempting to describe what will happen going forward over the next century or two is much more difficult. In order to simulate future climate, one employs so called General Circulation Models (GCMs), which are frequently referred to as "climate models" (for a survey of their use in economics, see Auffhammer et al., 2013). These models simulate the impact of different future emission paths greenhouse gases (e.g. CO_2, methane) and aerosols (e.g. dust and air pollution) on the climate system. Most economists have focused on the role of changes in temperature, but these detailed models produce predictions of precipitation, humidity, sea surface temperatures, and sea levels to name but a few variables. Output from these models is publicly available from the IPCC, yet in formats that are difficult to process. Also, the "official" climate model output available through the IPCC is not downscaled to a level of geography useful to economists. There are several efforts underway to make this information available in a usable format (e.g. https://www.impactlab.org; https://climexp.knmi.nl/). These products allow researchers to produce projections of changes in economically relevant variables (e.g. daily min/max temperatures, precipitation and relative humidity), which can then be used with estimated damage functions to project economic impacts of climate change.

It is impossible to summarize the state of climate science, but the summary for policy makers of the 5th Assessment report of the IPCC is a great start (IPCC, 2013). The degree of climate change depends crucially on the future trajectory of greenhouse gas emissions. The two extremes considered by the IPCC characterize two possible worlds – RCP 2.6 and RCP 8.5. RCP stands for representative concentration pathway, leading to an increase in radiative forcing (2.6 or 8.5 Watts per m^2). In language that economists can understand, these are two scenarios with very different underlying emissions pathways. The first (2.6) is consistent with radical reductions in emissions with negative annual emissions around mid-century. The second, RCP 8.5 is a somewhat aggressive business as usual emissions scenario consistent with continued rapid growth of emissions.

The difference in impacts is drastic. The RCP 8.5 scenario results in a significantly hotter world, where major crop growing regions are expected to see increases in surface temperatures in the range of 4–6 degrees Celsius. If you consider wheat growing areas for example, Russia, North America, and Australia are all expected to see significant warming, which is projected to result in depressed wheat yields. If major producers are negatively affected, an inward shift of the supply curve will result in higher prices, which translates into welfare changes across the world. The elasticity of demand for wheat will play a key role in determining equilibrium price changes. This elasticity is a function of the availability of wheat substitutes. Higher prices are good if you are producer, but bad if you are a consumer. As food markets are closely linked across the globe, changes in one region might have significant ramifications for the welfare of market participants elsewhere.

Predictions for rainfall patterns are more difficult. Overall there is more model agreement since the last IPCC assessment report, yet the predictions do not fully agree across models. In general the current best available science suggests that higher latitudes are in general expected to be wetter and hotter.

In this review, we will focus on the challenges climate change poses to the Least Developed Countries. While the IPCC assessments provide global and regional assessments, they do not break up the world along the same dimensions an economist would. It is an empirical regularity, that countries with warmer climates have lower per capita GDP in the cross section (Dell et al., 2012, 2013). This cross-sectional relationship cannot be interpreted as causal, as there are many other determinants of per capita GDP leading to this observation. One question one may ask is whether climate change will "level this playing field" by warming rich countries more than poor countries.

The first question we investigate is whether this cross sectional observation holds. Using an ensemble of climate models from the IPCC's fourth assessment report, the World Bank provides projections of temperature and precipitation for a large suite of climate models by country out to the end of the century.[1] We match these country level projections with per capita GDP in 2010 US$ and the share of value added from agriculture. Fig. 1 plots this cross-sectional relationship between the log of current per capita real GDP and future temperature. Specifically, we plot the median temperature prediction across climate models for a business as usual emissions scenario (IPCC A2) for the period 2080–2100 against 2010 per capita income in 2010 US$. The widely observed negative correlation between per capita income and future temperature holds. A regression between the two variables indicates that for each US$ 10,000 higher current day GDP the expected temperature is 1.41 degrees Celsius lower. This figure does not display the impacts of higher future temperatures on per capita GDP. This is the subject of a lively recent literature (see Burke et al., 2015; Dell et al., 2012, 2013).

One obvious question is whether poor countries are more likely to experience greater *increases* in temperatures than rich countries? Using World Bank Data, the source for Fig. 1, we plot the median climate change prediction across climate models for the high emissions scenario A2 for the period 2080–2100 against 2010 per capita income in 2010 US$.

[1]More recent country level projections based on CMIP5 for temperature and precipitation are not readily available at this point.

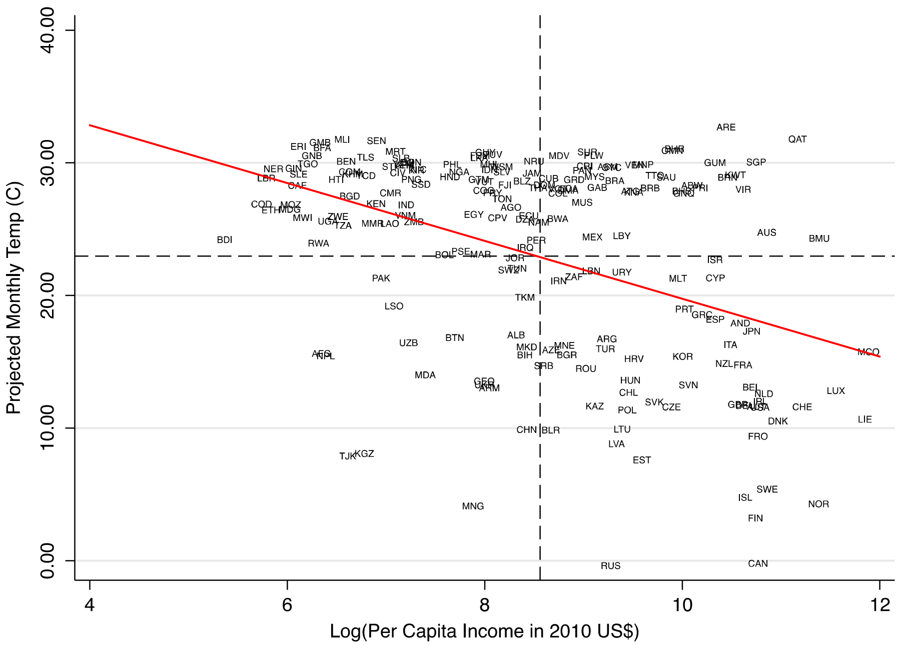

FIGURE 1

Projected 2080–2100 temperature against per capita GDP.

What Fig. 2 shows is a cloud of data with a slight negative correlation between both precipitation (left) and temperature (right) *changes*. The correlation between temperature change and log income is not statistically significant. The correlation between precipitation change and income is statistically significant. This suggests that lower income countries are predicted to experience slightly more warming and higher precipitation than higher income countries. What is more important to note is that while some countries are predicted to be drier and some are predicted to be wetter, the predictions for the temperature are positive across the board. All countries will be hotter. The question is by how much. The IPCC observes that model agreement for the temperature predictions is significantly greater than model agreement for the precipitation predictions. But this simply means that we cannot say with much certainty which places will get wetter and which place will get drier, but there will be both. For temperature, the prediction is clear – it will get hotter for everyone – on average and in the extremes. This is an issue as least developed countries are thought to have a lower adaptive capacity and worsen observed disparities (Burke et al., 2015). This is further significant, as future population growth is expected to be greatest in sub-Saharan Africa, which includes most of the LDCs (see Tilman et al., 2011). This could amplify many of the projected economic effects of climate change.

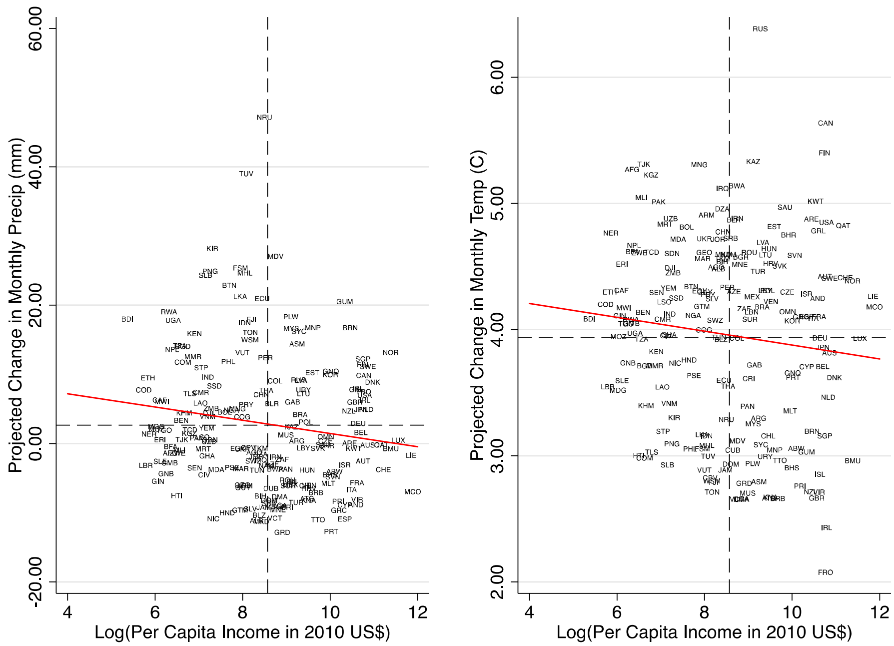

FIGURE 2

Projected changes in precipitation and temperature against per capita GDP.

We repeat the same exercise for share of value added from agriculture in Fig. 3. The pattern that emerges is not surprising as share of value added from agriculture and per capita GDP are highly negatively correlated (−0.84).

The image displays a positive, and in the case of precipitation, statistically significant positive correlation between share of agriculture in GDP and the two climate outcomes. Every country will be warmer, with the average warming under the business as usual A2 scenario here predicted to be 4 degrees Celsius (7 degrees Fahrenheit). In the case of precipitation, the average change is very close to zero, with massive variation in terms of sign and magnitude.

Overall, what this suggests is that while every nation is getting warmer, lower income countries on average will experience incrementally more warming – off an already warmer baseline. It is hence of key importance to empirically document the relationship between climate and agricultural outcomes flexibly across the temperature spectrum and by region/country. In the next section we will describe the different ways of estimating the relationships between different agricultural outcomes and climate.

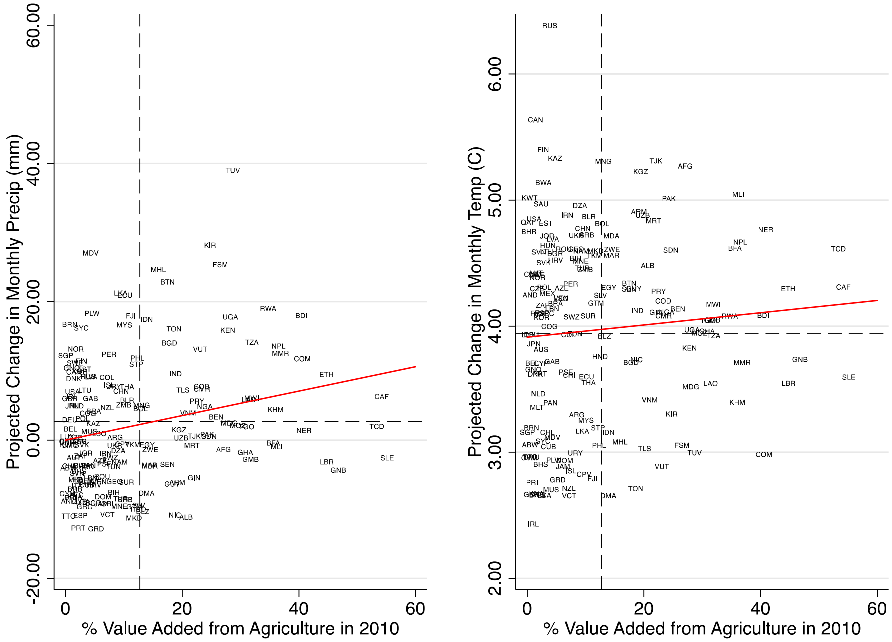

FIGURE 3

Projected changes in precipitation and temperature against agriculture share in GDP.

3 ESTIMATING THE IMPACTS OF CLIMATE CHANGE ON LDC AGRICULTURE

Farmers facing more frequent and intense climate shocks will be more likely to suffer from bad harvests (Seo and Mendelsohn, 2007). Those who raise rural livestock will face increased risk of animal death and malnutrition (Seo and Mendelsohn, 2008). The combination of frequent drought and extreme heat in many LDCs raises the chance of large income losses and, in many places, consumption dropping below subsistence levels. A recent empirical literature seeks to quantify how farmers are affected by anticipated and unanticipated climate shocks. A challenge for the econometrician, but a potential benefit for the farmer, is that there are a number adaptation strategies to self-insure against climate risk. In order to estimate the effect of climate on farm outcomes, the researcher would ideally like to observe a large sample of otherwise identical farmers growing the same crop in randomly assigned climates over time to identify a crop specific "dose response" of climate outcomes on a given crop's yields and net profits.

In reality, farmers do not necessarily stay put or continue farming the same crop in a world with a changing climate – they adapt. The farmer might switch crops, opt out of farming altogether and move to another geographic rural or urban area. Measuring this adaptation response is of key importance when one is interested in quantifying the damages from climate change going forward. The magnitude of this adaptive response, especially for the rural poor, depends crucially on the formation of expectations, available information, and access to human, physical and financial capital.

For any given hazard, spatial and temporal variation in the outcome and its drivers offers the opportunity for studying the consequences of changes in environmental conditions. An emerging literature has focused on estimating the impact of climate and weather on a variety of agricultural outcomes. Consider the following setting in a pre-climate change world. $\boldsymbol{w}_t$ is a vector of weather realizations a farmer faces in a given season. This vector could be a measure of temperature, precipitation, humidity and wind speed over a short period of time, like a single season or year. In most empirical settings this measure of weather is recorded as the average value of each indicator over the entire season or more highly resolved measures such as the counts of days the e.g. daily average temperature falls in certain quantiles of the temperature distribution. The key is that the measure is defined over a relatively short period of time. In a pre-climate change world, these weather realizations are drawn from a distribution. Moments of this distribution generating weather are commonly referred to as "climate". The most common use of the word "climate" in the literature is using 30-year averages of the weather observations. Hence a vector of climate variables $\boldsymbol{c_o}$ represents the long run average of a vector of weather indicators $\boldsymbol{w}_t$. Note that this weather indicator itself does not have to be an average *annual* temperature, but could be a seasonal temperature, growing degree day measures or any set of more complex indicators of weather.

Assume that the farmer has an area of land a_t. She makes a decision each period as to crop choice, inputs and technology based on her expectations of the discounted stream of net profits from her activities. This is a difficult problem, which has received massive amounts of attention in the agricultural economics literature. In a world without climate change, this problem has been comprehensively studied (Mundlak, 1963, 2001). It is instructive to discuss the basic problem here as this farmer will face a changing climate and hence has a more complicated decision to make as climate is no longer a stationary variable.

At the beginning of each season, she has to choose which *use* to put her land to. She could choose between planting one or multiple crops (farming), using the land for raising livestock, or not farm it and put it to an alternate use. She also has to choose which *technology* to use to grow the crop she chooses. Many crops like rice, require special investments in the fields themselves so they can be flooded. A farmer at the beginning of the season does not start from scratch. The fields were used to grow something in the previous season(s) and fields and technology were chosen over a long period of time to best match the chosen crop. Making changes to fields or investing in new technologies requires often significant fixed costs initially as well as variable costs to use them during the season (e.g. electricity to operate pumps). Hence changing from one use to another is costly and those costs can be non-trivial.

So at time t, the farmer has to form expectations of future profits. Let's at first simply think about this for a single season. The farmer has to form expectations about the price each crop will get at the end of the season. We can think of a simple process whereby the farmer forms price expectations based on the prices crops received in the prior year and possibly taking into account any announced government support prices. Expected revenues hence depend on expected input and output prices as well as expected output for each crop planted. Output is a function of the physical inputs used for production, such as land (a_t), capital (k_t), and labor (l_t) as well as other inputs (i_t) such as fertilizer, pesticides and irrigation water. Of course, in agriculture as in many other sectors, a major input which is beyond the farmer's control is the weather ($\boldsymbol{w}_t$) during the growing period. A production function can then be expressed as $q_t = f(a_t, k_t, l_t, i_t, w_t; \boldsymbol{\theta}_o)$. There are many types of production functions used in practice, such as Cobb–Douglas, CES, and Translog. It is of course important that the functional form used reflect properties of actual crop production, but we want to focus on the parametrization of the production function here instead of the choice of functional form. For a given stationary climate, farmers optimize their production technology accordingly, which here we denote as $\boldsymbol{\theta}_o$. This technology, of course can have crop specific features (e.g. growing rice requires irrigation infrastructure in many settings).

The expected end of season profits depend on end of season realized input costs (e.g. labor, capital, fertilizer, pesticides, irrigation) r_t and if the farmer chooses to switch crops, possible adjustment costs for installing the new necessary capital or any other transaction costs i_t. A single period static profit function could be written down as:

$$E(\pi_t) = E[\boldsymbol{p}_t \cdot \boldsymbol{q}_t - r_t - i_t]$$

In a stationary climate, there are year to year fluctuations in weather, which will affect physical output (e.g. a hot year may retard plant growth), input prices and use (e.g. increased demand for inputs may drive up their prices), and output prices (e.g. a hot year with low output combined with low aggregate storage levels may drive up output price). Weather shocks hence affect output directly through physical impacts on agricultural output and livestock productivity and survival rates and indirectly through input and output prices. Variation in weather hence leads to well documented variability in farm profits across seasons.

Also, in much of the developing world not all output is sold by each farm. In many settings part or all of the crop the farmer grows is consumed by the farm household or traded for other goods and services within the local community. In this stationary climate setting there will be year to year fluctuations, which farmers will respond to by taking actions to maximize expected profits throughout season (e.g. apply additional irrigation water, fertilizer, pesticides, labor).

Using well documented econometric techniques from the literature in agricultural economics, one can parameterize the profit or a production function, provided one has data with a sufficiently large degree of variation. The estimated coefficients from these regressions capture the short run responses in the outcomes of interest to fluctuations in input, output prices, and weather (Mundlak, 1963, 2001).

3.1 THE IMPACT OF CLIMATE CHANGE ON A FARMER'S INVESTMENT DECISIONS

The increase in anthropogenic emissions of greenhouse gases causes gradual changes in climate, such that the vector of climate $\boldsymbol{c_o}$ changes to $\boldsymbol{c}_1$.[2] This changing climate regime will permanently shift the weather distribution. This could be a mean shift only or a change in higher order moments of the weather distribution. If the farmer does not learn about the change in climate, but assumes that she still faces the old climate regime, she will use the old technology $\boldsymbol{\theta}_o$ to produce her output and produce a suboptimal level of output as the technology is not optimized for the new climate regime. If no one learns, each farmer will continue to produce using the wrong technology, which will lead to suboptimal output of the crop in the long run. This is sometimes called the "dumb farmer" assumption. This is not a tenable assumption in the long run.

If the farmer learns that climate has shifted, (s)he will re-optimize and shift her production technology to $\boldsymbol{\theta}_1$, if the benefits from doing so outweigh the costs of doing so. If they do not, the other explanation for observing farmers producing output with the "wrong" technology is the possibility that the costs of switching technology are greater than the benefits (e.g. higher yields) from doing so, so it may be perfectly rational for the farmer to produce with $\boldsymbol{\theta}_o$ – even in a new climate regime (Quiggin and Horowitz, 1999).

If the benefits of the technology outweigh the costs, the farmer adopts the now optimal technology for the new climate regime. This could entail the installation of irrigation equipment, a switch in the type of crop planted etc. to maximize expected profits for the farmer. This change in technology from $\boldsymbol{\theta}_o$ to $\boldsymbol{\theta}_1$ is often referred to as adaptation to climate change. It is important to note that this change in technology can change both the output-climate relationship as well as the input-climate relationship (e.g. installation of irrigation infrastructure leads to increased use of irrigation water). This behavior is distinctly different from the within season response to weather shocks. For example, if a farmer experiences a relatively hot and dry year, she may apply less fertilizer that year as high concentrations of fertilizer can "burn" plants. However, if the farmer learns that the climate has changed and that the frequency of hot dry years will go up significantly in her area, she may respond by installing irrigation infrastructure. This has often been described as the difference between the weather sensitivity and the climate sensitivity of a sector. Any credible study that estimates the impact of climate change has to deal with the issue that long run (climate) and short run (weather) responses of sectors are different and it is the long run sensitivity that should be used in climate impacts estimation.

One other important dimension of looking at farmers has to do with the fact the decision the farmer has to make in year t is not a static decision, but a dynamic one. In reality, the farmer has to form her expectations over the random variables (prices,

[2] In practice climate change is gradual and will lead to slowly changing weather patterns over time. For simplicity, we stick to a discrete change in climate for this paper.

availability of inputs, costs and effectiveness of new technologies and climate) and discount the stream of expected future profits to determine the optimal investment and crop choice decision at time t. This is a much more complex optimization problem, that has been modeled extensively in the agricultural economics and development economics literatures (Mundlak, 2001; Moschini and Hennessy, 2001; Nerlove and Bessler, 2001).

A further, and maybe most challenging, complication is the fact that farmers are not necessarily risk neutral in the way they make decisions as we have implicitly assumed in our basic framework. In reality, most farmers are risk averse. Early work on these issues are Sandmo (1971) and Batra and Ullah (1974). The relevant literature in agricultural economics has been nicely synthesized in Moschini and Hennessy (2001).

A final important aspect is how and when the farmer learns about the fact that the climate has changed. The easiest way to think about this is to imagine that there is a mean shift in climate. Pre climate change the farmer has adopted a technology that allows for some flexibility in production as firms might want to produce a range of output depending on input prices (Stigler, 1939). Once climate changes, farmers need to learn that this happens and then adopt a technology that allows for their new preferred range of possible output. There is a big literature on adoption of technology in agriculture in an uncertain world, which is summarized nicely in Sunding and Zilberman (2001). Some recent work has looked at the issue of learning in the context of monsoon onset in Indian agriculture (Kala, 2015), which provides a nice entry point into the learning literature.

The simple model presented above is the assumed simplified data generating process underlying the data observed by the econometrician attempting to quantify the responsiveness of a farmer to changes in climate/weather. Over the past four decades a number of statistical approaches have emerged, each with their strengths and weaknesses. We summarize the main approaches here. Other detailed methodological reviews have been provided by Carleton and Hsiang (2016) and Dell et al. (2013).

The literature on climate change impacts on agriculture was started by using agronomic process based models of crops. This literature builds and uses complex computer models of individual plants' physiological processes. Modelers then use these "all knowing" models to simulate responses of different crops to climate stresses and simulate yield impacts (e.g. Rosenzweig and Parry, 1994; Rosenzweig et al., 2014). This literature, as it just focuses on plant behavior, largely ignores actions the farmer can take to offset adverse changes in the climate. Hence a social science literature has developed to incorporate the farmer and hence adaptation.

In the empirical econometrics literature, there are four categories of estimation approaches used in climate impacts estimation. The overarching goal is to estimate the impact of long run climate change on different economic sectors. Here we focus on agriculture literature only, since this sector is acutely climate sensitive. While it only accounts for 2% of global GDP, it produces the majority of the calories humans and their pets consume. We are not interested in how farmers respond to year to year

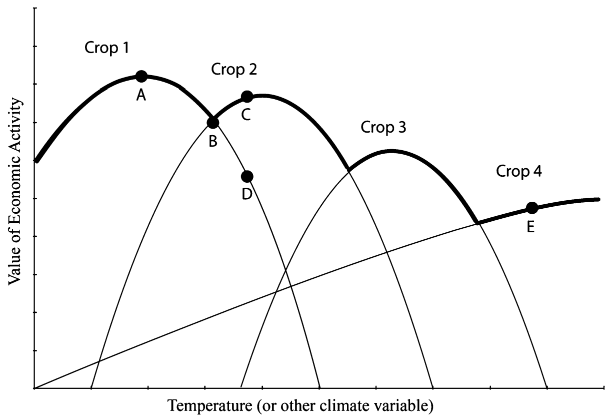

FIGURE 4

Crop choice and profits in the long and short run. Modified version of Fig. 1 in Mendelsohn et al. (1994).

weather fluctuations, as this does (in many settings) not account for adaptation. Below we describe the state of the literature for this application and point out explicitly which methods account for adaptation and which ones do not (also see Plantinga, 2017).

The estimation methods found in the literature vary by whether they actually estimate the impact of climate or weather on the agricultural outcome. Second, they vary by the type of variation used to identify climate/weather effects. Some use cross sectional variation only, others use panel data relying on within location time series variation to identify effects, which has consequences for the degree of causal inference in the studies.

The first class of models, which are by far the most widely applied in the literature in both the developed and developing country context, are referred to as Ricardian Models. Mendelsohn et al. (1994) exploit the fact that climate (the 30 year average of weather in a given location) varies across space – even in a stationary climate. Farmers in each location have hence optimized their local production technology/choice of crop according to the local climate. Fig. 4 illustrates their conceptual model's key ideas.

The insight here is that as climate shifts the temperature distribution towards higher temperatures, if you assume that technology stays constant (e.g. by estimating a single crop production function), one would drastically overestimate the impacts of climate change on the value of farming. For example, if a farmer who is growing crop 1 and currently producing at point B, faces a warmer climate and continues to farm crop 1, she will get D in profits. If she adapted to growing crop 2 she would get C in profits. This means that holding technology constant would overestimate the damages from climate change by C–D. The empirical model they derive from this insight is that if one observes a cross section of net profits and climate, one could regress net profits on climate and recover the climate elasticity of the agricultural sector. The key assumption here is that in the long run farmers have optimized to their local climate regime. This approach hence recovers the climate response by looking at the climate response across the cross section of individually climate optimized farmers. The advantage of this method is that it recovers an actual climate sensitivity, yet at a cost. As with all cross-sectional approaches, these regressions suffer from omitted variables bias (OVB). If, for example, soil quality is correlated with climate and one fails to control for soil quality in the regression, one would falsely attribute the effect of better soils to climate and bias the elasticity. Several papers point out the fragility of such estimates to OVB, the most well-known of which point out the importance of accounting for irrigation (Schlenker et al., 2005).

Other "Ricardian" studies set in developing countries quantify the sensitivity of the agricultural sector to variation in climate conditions (Kurukulasuriya et al., 2006; Mendelsohn and Dinar, 1999; Kurukulasuriya and Mendelsohn, 2008; Seo and Mendelsohn, 2008). One challenge facing these studies is the matching of the crop calendar to the climate outcomes. There is a vast crop and location specific agronomic literature that studies the importance of different environmental factors throughout the life cycles of different crops (Yoshida and Parao, 1976). It is hence important to use climate variables in regressions which match the crop calendar and possibly within growing season life cycle of crops. The vast majority of Ricardian studies simply uses quarterly averages, which is a naïve approach to specifying how climate affects yields, as different crops have different life cycles throughout the year. This introduces measurement error, which if classical, attenuates the effects of climate on yields. Recent work by Welch et al. (2010) has shown the importance of improving this temporal match. Further, most Ricardian studies use simple seasonal quadratics in the climate variables, which forces a symmetric response around an "optimal" temperature.

A more recent branch of the literature has tried to overcome the omitted variables bias critique of the Ricardian models. Ricardian models attempt to address the issue by explicitly controlling for any possible confounders correlated with climate and the outcome (e.g. yield, net profits). The argument against this has been that one cannot possibly control for all relevant confounders, as some are unobservable. Auffhammer et al. (2006) and Deschenes and Greenstone (2007) estimate panel data models by regressing measures of agricultural output (e.g. output, yields, net profits) on annual or within season weather outcomes across space and time. The regressions carefully control for spatial unit and time fixed effects to flexibly control for time varying confounders affecting all states/counties and unobservable differences across counties. Auffhammer et al. (2006) conduct this exercise for rain fed rice agriculture in India at the state level and abstain from a projection exercise in favor of a historical detection and attribution exercise. Deschenes and Greenstone (2007) use the estimated weather response coefficients to project impacts of climate change on the US agricultural sector out to the end of the century. Guiteras (2009) conducts a similar exercise for India's agricultural sector at the district level. Chen et al. (2016) provide a study for China. What many of these studies have in common is that they all use flexible functional forms for the temperature response, by binning the number of days a given area encounters in discrete temperature bins. This nonlinear functional form was pioneered in the United States by Schlenker and Roberts (2006, 2009). This overcomes the issue introduced in the Ricardian approach, where simple polynomials have been used historically forcing a symmetric response. For the four major crops (soy, wheat, cotton, and maize) it has been suggested that days with temperatures above 31 degrees Celsius result in significant yield losses. There is no evidence of such a threshold for rice. This approach has been applied widely not just to the agricultural sector but to farmer suicides (through a possible reduced yield channel) (Carleton, 2017), migration, mortality and macroeconomic activity more generally (Hsiang et al., 2017).

The significant drawback of this approach is that it uses the response of an entity to weather – not climate. A farmer's response to a single additional hot day in a season is very different than the same farmer's response if she expects there to be one more hot day per year in perpetuity. A short run response may be the temporary application of more inputs at the margin. The long run response maybe the investment in durable capital (e.g. irrigation infrastructure), change in crops, change in planting schedules, migration of the farm or the abandoning of farming activities altogether. Hence, studies using high frequency weather data will likely drastically overestimate the damages from climate change, since these studies ignore much of the long run adaptation.

A recent literature using quadratics in temperature combined with high frequency weather data as control variables finds that the use of polynomials allows for some degree of adaptation. The argument is two fold. First, if one uses fixed effects and a second order polynomial, the fixed effects demean the level and the square term, which makes the estimator use both within spatial unit as well as across spatial unit variation to identify the impact of e.g. temperature on the outcome of interest (McIntosh and Schlenker, 2006). Hsiang (2016) and Deryiugina and Hsiang (2017) in an application of the envelope theorem argue that using short run variation in weather is valid as long as all cross sectional units optimize their production according to their local climate.

A third, more recent innovation marrying the best of the Ricardian approach with the best of the panel data approaches was proposed by Burke and Emerick (2016) and is referred to as the long differences approach. For the US agricultural sector, they exploit the fact that we have long time series across counties of both outcomes and weather. They then regress the change in five year moving averages at the beginning of the sample to the end of the sample of the outcome of interest on the same long difference in weather. This removes county unobservable differences. This approach is made possible by exploiting variation in observed warming trends across counties. It requires long panels of outcomes and temperatures. The advantage of this method is that it sweeps aside the main OVB concerns and estimates a climate – not a weather – sensitivity. It is the best of both worlds and could be applied to developing country settings, where data are available. It is interesting that for North America, they find little difference in short run (weather) and long run (climate) impacts on the main food crops, which they suggest is consistent with a very small or limited degree of adaptation. Shrader (2017) points out the importance of how agents form expectations about future climate and questions whether one can use historical data to study the adaptation response to *expected* climate change. In order to do this correctly, one would want to study the adaptation response to expected climate change of agents. More broadly, however, what the literature has failed to do so far is to detect specific evidence of adaptation at the field level (e.g. change in cropping patterns, planting calendars, crop mixes) and analyze the effectiveness of these adaptation mechanisms. If there really is, like Burke and Emerick suggest, no adaptation taking place, we need to better understand why that is the case. Specific areas ripe for research should focus on the role of information, credit constraints, and government subsidies.

A fourth approach, which is more recent and has high data requirements builds on the panel data approach proposed by Auffhammer et al. (2006). If one can estimate temperature response equations for different areas (e.g. ZIP codes, counties) one can change the shape of the dose response function empirically. The first evidence of this was proposed by Auffhammer and Aroonruengsawat (2012) for electricity consumption and Butler and Huybers (2013) for agriculture. These papers estimate the dose response functions for different areas (e.g. ZIP codes, counties) or time periods (1960s, 1990s) and look for differences in the dose response as a function of differences in climate during the time period or across spatial units. Auffhammer and Aroonruengsawat (2012) use detailed micro datasets on household electricity consumption to estimate the causal short run response to temperature at the ZIP code level. They then explain cross sectional variation in electricity temperature response across ZIP codes as a function of climate. They then link these equations to state of the art downscaled climate models and calculate projections of impacts of short and long run response. Butler and Huybers (2013) adopt a similar approach by letting the dose response function change over time, as there is warming in the later part of his sample. To the best of our knowledge this has not been applied in the developing country context. This has much to do with data availability. As more high resolution global daily weather data come online (e.g. Berkeley Earth Project), it should be possible to conduct more of this type of research in the developing country context.

Next, the literature focuses on the main food crops (soy, rice, wheat, maize) and cotton. We know little about the climate sensitivity of food crops important in large parts of the world (e.g. millet, taro, cassava). It is paramount that we better understand the climate response of these important crops.

Finally, none of these approaches measure the cost of adaptation (i_t) (Plantinga, 2017). If the goal of the economist's exercise is to derive the monetized effect of climate change on agriculture, then adaptation costs should be included. There is a current effort underway to develop methods to do this for mortality out of Chicago's climate impact lab, but no public papers were available at the time of the writing of this chapter.

3.2 AGGREGATION AND GENERAL EQUILIBRIUM EFFECTS

Many econometric studies examining global climate change impacts struggle with incorporating general equilibrium effects. If climate warms and yields drop everywhere or in a majority of crop producing regions, prices will change, which will invalidate the partial equilibrium simulation results of all of the studies cited above. Roberts and Schlenker (2013) and Lobell et al. (2011) provide one avenue to identify global general equilibrium effects, but more work needs to be done on this topic. If we view climate shocks as "supply shifters", then the elasticity of demand for a given agricultural good plays a central role in determining general equilibrium effects. Given that agricultural produce is heavy to ship and can be stored for a finite amount of time, both spatial arbitrage considerations and intertemporal storage (i.e. Hotelling's law) will have implications for how a shock at a point in time and space ripples through the economic system. One path forward is recent work that involves an effort to merge findings from econometric yield impacts models and the GTAP model (Moore et al., 2017).

The general equilibrium effects of local weather will also depend on government international trade choices over tariffs and quotas. Imagine a small LDC nation whose leaders choose to have no trade barriers for agricultural goods. In this case, the nation's farmers compete with world exporters and urban consumers are insulated from local climate shocks (Glaeser, 2014). If climate change lowers the nation's farm output, the farmers do not receive higher prices for their produce. Instead, they grow less and receive less income. Many developing nations enact agricultural trade barriers. These barriers provide some monopoly power for domestic farmers and this means that urban consumers face more volatile price dynamics as a function of local climate conditions.

Going forward, as scientists devise new resilience strategies and technologies, how quickly will they diffuse across poor farmers? What are the impediments slowing down such a transition? Field experiment research designs are the ideal research tool here. Conley and Udry (2010) present findings on the diffusion of information within social networks. In growing pineapples, farmers imitate their neighbor's successful strategies. Work done by Kyle Emerick and coauthors pushes the envelope in important dimension of the literature, which is how to deliver a new climate resilient technology to the farmer. He looks at the yield benefits of submergence resistant rice varieties in South Asia (Dar et al., 2013). They show significant yield benefits of these new varieties when rice is submerged for up to 10 days with no yield penalty when there is no submergence – a win-win. In a second study he studies how to get new seed varieties to farmers. He randomizes how this successful new technology gets dispersed among villages – via salesperson or through farmer social networks and shows evidence of significant under adoption in the farmer networks (Emerick, 2018).

4 THE FARMER CLIMATE ADAPTATION CHALLENGE

Fig. 4 implicitly assumes a frictionless transition as land is redeployed from one use to another as the climate changes. In reality, both time and resources must be spent to bring about this transition such as reallocating land from wheat to corn. These transition costs are likely to vary across space and across farmers. While the land will eventually be allocated to its new highest and best use, there will be distributional consequences involved in this transition. What happens to the original user of the land parcel? Does she sell the parcel to another user who has a comparative advantage in coping with the new climate conditions? Does the original farmer find a way to redeploy her capital and skills that she used to grow the original crops or are these sunk costs that must be included in the cost of adaptation? If the new best use of the land features a fixed cost to implement, will small farmers be able to finance these? These questions highlight that climate change will have important distributional consequences across farmers. Each of these questions merit future research.

We start by discussing property rights. If the property rights for farmland are well defined and costlessly enforced, then the land market will allocate this scarce resource to its highest use. Those with a comparative advantage at coping with new climate conditions will acquire access to these lands (assuming they can borrow on capital markets) and the land will make the efficient transition. In reality, much LDC land is not formally titled and the rule of law is weak. In such a setting, classic "Tragedy of the Commons" issues arise. Farmers and those with livestock may seek to move onto other more productive lands. Such a threat of encroachment will lead incumbents to take costly self-protection actions to secure their property (Fields, 2005). This investment of time and resources in repelling the threat of encroachment is another adaptation cost that should be factored in determining the cost of adaptation. If rural people face subsistence level constraints such that they starve if their caloric intake falls below some minimum level, then violence may emerge as an equilibrium in the countryside as desperate people hunt for increasingly scarce resources (Glaeser, 2014). Repeated social interactions between long term neighbors builds up trust and social capital and this helps to attenuate the Tragedy of the Commons problem (Ostrom, 2010). Whether such "neighborly good will" holds up under the pressure of increased climate variability is an important future research question.

Recent research has examined the link between climate change and rural violence. Cross-national research based on panel data from 1980 to 2005 in Sub-Saharan Africa has documented that the probability of civil war is higher in nations experiencing hotter summers (Burke et al., 2009; Hsiang et al., 2013; Hsiang and Meng, 2015). For violence to erupt suggests that rural people have few coping strategies and are desperate to find food and shelter. More recent research has studied the impact of higher commodity prices on conflict. McGuirk and Burke (2017) document using commodity pricing for the entire African continent that rising world commodity prices reduce violence among producers due to an opportunity cost effect while violence among consumers increases.

4.1 INCOME INEQUALITY AND CLIMATE CHANGE

An important open research question is whether climate change will increase overall income inequality. Sala-i-Martin (2006) has argued that global inequality is falling because of the reduction in poverty in the developing world – especially in highly populated nations such as China and India. If, however, the poor in LDCs have little ability to cope with climate change, then such shifts will increase a poor nation's income inequality.

Subsistence farmers may suffer large income losses due to climate change. Consider a case in which given a new climate, corn is now the right crop to grow on a specific parcel. Small farmers may not have the physical, financial or human capital to make this transition. In this case, larger farms are likely to have market power in negotiations and purchase the land at a lower price from the small farmer. This example highlights how the industrial organization of LDC farms may change due to climate change. In this case, the land will be efficiently repositioned but the incumbent farmers will be displaced and receive a low rate of return on their land assets.

Sugar represents a prime example. This is a crop that is more efficiently grown on larger plantations. Historical research by Sokoloff and Engerman (2000) shows that in Brazil the agricultural sector featured large land holdings because of scale economies. This structure of property ownership led to an inequality of income and this inequality persists over time. Acemoglu et al. (2001) argue that nations with more income inequality feature an elite who use their political power to create extractive institutions that transfer more resources to the elites. A human capital theory would posit that those farmers with higher incomes will invest more in their childrens' human capital and this boost in skill formation will form the basis for a persistent intergenerational correlation of income. Both the "extraction" theory and the human capital theory imply that climate change will exacerbate an agricultural nation's income inequality in the long run.

To test these claims, researchers would need to study how parcels of land are being aggregated and who owns them over time as climate conditions change. Are farms becoming bigger (Jayne et al., 2003)? Do small farmers sell their land for low prices and then transition to low paying jobs?

So far, this discussion has focused on how individual farmers cope with a changing climate. A recent US climate literature has focused on how rural places cope with change. Research in the United States has projected how climate change will increase cross-county inequality in per-capita income (Hsiang et al., 2017), albeit not taking into account full adaptation. Other research has examined how the Dust Bowl was affected by the natural disasters it faced in the 1930s (Hornbeck, 2012). Similar work studying the long run consequences of natural disasters for places in the developing world would be quite valuable. For example, the impact of the 2004 Asian Tsunami has been studied in several papers (Gray et al., 2014; Gillespie et al., 2014).

4.2 LDC FARMER CLIMATE CHANGE ADAPTATION OPPORTUNITIES

Investment in human capital facilitates adaptation through several different channels. The skilled are more productive in both the rural and the urban sector. The educated are more likely to be literate. Those with more cognitive capacity will be more likely to anticipate emerging challenges and to react sooner and more creatively to emerging challenges (Becker and Mulligan, 1997). The behavioral economics literature also predicts that those with more human capital will be more likely to detect that the climate is changing (Benjamin et al., 2013).

The rise of rural education efforts reduces rural poverty (Jensen and Miller, 2017). If low levels of education cause impatience and an inability to solve problems and anticipate emerging trends, then rising education can help the poor farmers be more nimble in the face of a changing climate (Benjamin et al., 2013).

Recent research has used natural disasters as natural experiments to test how rural households reallocate childrens' time when the returns to farming are low. Shah and Steinberg (2017) document in rural India that childrens' educational attainment rises when disasters occur. This work highlights that parents are aware of the benefits of education and are responsive to opportunity cost.

The Big Data revolution raises new adaptation possibilities for LDC farmers. As remote sensing technology improves, geographers have an increased ability to create spatially refined data that can be used to provide customized information to farmers. Given that information can be a public good, development economists could educate farmers by providing land "report cards" to farmers to nudge them to consider shifting their lands to higher value uses.

More spatially refined data on the quantity of rainfall will play a key role in the creation of weather insurance markets. A buyer of a weather insurance contract would receive a payoff if there is extreme temperature or rainfall or drought at a specific monitoring station. Such a contingent contract would provide income to the farmer in "bad states of the world". One challenge with specific farmers using such markets as a risk hedging approach is that these weather monitoring stations are sometimes far from the actual plots of land. This means that the insurance payoff is less highly correlated with the actual climate conditions experienced by a specific farmer's plot of land (Mobarak and Rosenzweig, 2013). The value of such weather insurance increases as the volatility of shocks increases.

A third adaptation strategy is the rise of the adoption of GMO technologies (Qaim and Zilberman, 2003; Barrows et al., 2014). While there are many unsettled scientific issues here, GMO varieties such as heat resistant wheat offer to the farmer the possibility of facing less crop loss when extreme weather events occur. If these technologies deliver as promised, an open question is whether such technologies will be affordable for both small and large farms. It is possible that only large farms will adopt these technologies. In this case, the smaller farmers' land will be consolidated into larger farms and the physical place will adapt but the original small farmers will have to transition to a new way of life. The economic and personal costs of such a transition must be counted as part of the cost of climate adaptation and have implications for the extent that the poor bear the greatest costs from climate change.

This point must be caveated by recognizing the income effect when a poor farmer sells his land to a large "GMO farm". The ability of the small farmer to recover from the original weather change hinges on the terms of the deal. If the large farm buys the small farmers out with very low payments because of asymmetries in bargaining power then the local land will be redeployed, but the original farmers face even greater poverty risk. This example highlights that land markets break the link between how places and people are affected by persistent weather shocks. Dating back to work on California's Owens Valley, there has been the concern that small farmers lose out in land negotiations (Libecap, 2007). Whether such a dynamic will play out in different developing nations will be an important research question with clear equity implications.

4.3 RURAL DATA COLLECTION NEEDS TO ACCELERATE ADAPTATION RESEARCH PROGRESS

The building blocks for studying rural dynamics in the face of climate change will be a matched panel sample of farmland and farmers. Starting in a base year, a researcher would need to observe for each parcel of land, what it is being used for, who owns it, who manages it, and what is the land's current productivity. Such data would allow the researcher to test for interesting heterogeneous treatment effects. Different farmers might respond to the same climate shock by moving along different margins. Some might adjust by switching crops while others might sell their land to a larger farm. These data would permit an accurate portrayal of the land use dynamics and what happens to the farmer. Such a data set could be assembled by combining remote sensing data by land parcel with surveys of the farms to collect data on outputs and inputs and other farm geographic variables. The greater data challenge would be to track people over time such as those that leave a specific farm to move elsewhere or to a city. In this cell phone age, an individual's co-ordinates could be tracked and this would create a way to study the life path for individuals who leave a specific parcel of land.

Such a matched data set would be the analogue of the data creation strategy used by labor economists in the US and Europe (Abowd and Kramarz, 1999; Abowd et al., 2006). In the US, matched firm/worker data sets allow one to study how the firm's average worker changes over time due to hires and separations. In the labor economics literature, economists exploit natural experiments such as a factory closing to examine what are the subsequent labor earnings dynamics for workers who lost their jobs. Such income dynamics speak directly to capturing how nimble on net different individuals are. For workers who leave a firm after the firm closes, researchers study how the earnings of displaced workers are affected (Jacobson et al. 1993; Davis and von Wachter, 2011). The distributional effects of sectoral change can be explored by studying the quantiles of the change in earnings say two years after the displacement shock.

This natural experiment research design is highly relevant for studying farm land and farmer income dynamics. Researchers could study how natural disasters or shifting climate conditions impact a farm's overall profitability, output, and labor force changes. Using this research design, one can study the gross flows of workers both joining the farm and the subsequent outcomes for those workers who leave the farm.

If such a panel data set could be created, then researchers could implement randomized field experiment designs to randomly assign treatments such as free transportation or the first year urban rent to be paid to test how such treatments work to attenuate the negative effects of natural disasters and extreme climate events (Bryan et al., 2014a). This work would be analogous to the famous Move to Opportunity experiments in the United States (Chetty et al., 2016). By encouraging LDC farmers to move, do outcomes for them and their children improve? Such experimental evidence would be directly relevant for judging the importance of overcoming frictions that inhibit migration. Gray and Mueller (2012) study the impact of natural disasters on population mobility in Bangladesh. Past research has argued that social capital anchors farmers in the countryside (Banerjee and Newman, 1998). How large must urban/rural income differentials be to stimulate migration remains an open question (Young, 2013).

4.4 RURAL TO URBAN MIGRATION AS AN ADAPTATION STRATEGY

A researcher who has longitudinal data for a large set of farmers will observe some of them move to cities. If a data set could incorporate information on where the new urbanite lives, what industry and occupation the person works in, then this data collection effort yields a detailed picture of how the former farmer's quality of life has been affected by the rural to urban transition.

Migration from the countryside to a city represents a risky investment. In the classic Harris and Todaro (1970) and Sjaastad (1962) models, the migrant incurs a fixed cost for leaving one's origin. This fixed cost may reflect both financial costs of leaving and also the psychic cost of leaving one's rural social network (Banerjee and Newman, 1998). In a LDC context, climate shocks may set off large migration flows as many people seek to exit the rural sector. Key issues arise concerning the ability of urban areas to cope with a sudden influx of migrants. The ability to migrate will be determined by liquidity constraints, perceived opportunities in cities and the human capital and imagination to consider making such a key life choice (i.e. moving to a distant city). A key issue arises concerning the timing of such migration, if some farmers figure out early on that the climate is changing then they will be more likely to move early and the process of rural to urban migration will be more orderly. Conversely, if farmers only migrate after the realization of a climate shock, then the transition dynamics will be much more costly for the destination areas.

This discussion points to several promising research areas. Recent work in Bangladesh has used a field experiment design to demonstrate that transportation costs limit migration. When free bus passes were provided, farmers send young adults to the city to work and this urban income was remitted back to the countryside. This income portfolio helped the rural family to smooth consumption during a time of low farming productivity (Bryan et al., 2014a). These results have important implications for climate adaptation if climate change increases the volatility of weather conditions.

It is easy to state that the risk neutral rural farmer will urbanize if the expected present discounted value of moving to the highest paying city net of rents is greater than the opportunity cost of continuing to farm plus the migration cost. Yet the difficulty here is how to operationalize this concept. Both the individual farmer and the econometrician, who seeks to study the farmer's adaptation efforts, face the challenges of: 1. Estimating future income of remaining in the countryside, 2. Estimating the probability of finding a job and the wage in each potential destination city, 3. Estimating one's earnings profile over time and rents paid in each potential destination city, 4. Measuring the non-market quality of life in each of these cities.

Only by constructing the farmer's actual budget set, can the econometrician recover the tradeoff that the farmer faced at the point when he chose to move. To appreciate this point, consider the study of Avery et al. (2012) in investigating college choice. Since they were able to observe the actual scholarship tuition deals offered to each student, they were able to reconstruct the actual choice set that students faced. A researcher who simply observes a student's college choice and the "sticker tuition price" of each school would not recover the student's actual willingness to tradeoff university attributes such as school quality versus actual tuition. Recognizing this point, researchers have estimated reduced form regressions studying how migration patterns to LDC cities are affected by origin climate conditions (Barrios et al., 2006).

4.5 THE DIMENSIONALITY OF THE LDC MIGRANT'S URBAN CHOICE SET

In LDC nations featuring more cities, migrants will have a larger choice set. Such a larger menu of possible destinations offers more adaptation possibilities. These cities will differ with respect to their industrial composition, congestion, and housing conditions as well as their proximity to the migrant's origin location. For young, less educated rural people, they will be more likely to find gainful employment in cities if the cities are industrializing. Manufacturing is a sector whose output is less likely to be positively correlated with agricultural production. Recent research by Henderson et al. (2017) studies African urbanization and finds that 75% of the cities in these nations specialize in agricultural "middle man" services. This means that there is a positive correlation in income between Africa's rural and urban areas. Thus, when the rural country side is suffering from low harvests and the farmers increasingly seek to migrate, the majority of the cities are suffering from a recession as well. The spatial diversification gains from urbanizing are larger if the city's economy specializes in industries whose output is not correlated with agricultural production. While Deichman et al.'s research takes the industrial structure of African cities as exogenous, this raises the question of whether more African cities will make a transition to being manufacturing centers because climate change poses a risk to core incomes?

In recent years, there has been a backlash against international migration. Some nations in Europe such as Germany have received a huge influx of migrants. Some nations have responded by erecting limits to such international migration. These barriers to international migration raise adaptation costs for rural people in the developing world as they lose possible adaptation pathways. A structural researcher could estimate this cost by estimating the expected utility of a migrant as the number of possible destinations shrinks (due to immigration constraints). An open question concerns the incentives of destination nations such as European nations to be more open minded in receiving refugees. Ongoing research in mechanism design is needed to design incentive compatible rules that encourage migration to areas more willing to accept new migrants (Delacrétaz et al., 2016).

The current backlash against international migration inhibits the ability of LDC rural people from moving to cities in Europe and other richer areas. In smaller nations with fewer cities, rural people will have fewer destination choices (Alesina and Spolaore, 1997). Environmental scholars have argued that the dislocation caused to destination nations by such flows portends future trends as "environmental refugees" will also seek safe havens. While the refugee challenge is clear, it is important to note that such migrants have strong incentives to seek out local labor markets where their skills are in demand. For example, if there is a city seeking low skill workers and wages for such workers are high, this is a clear price signal that this city seeks more of such workers to move there. In this sense, market price signals will direct the "refugees" to destinations where their effort is most highly valued. The allocative mechanism of capitalism thus plays a key role in reducing the costs of sector adjustment induced by climate change.

During a time of declining support for international migration, the possibility of creating more potential destination cities within nations would appear to be of increased importance. Fuller and Kahn (2013) discuss the climate adaptation opportunities created by the opening of new cities. While there would be fixed costs to create such cities, they can be operated under new rules because there are no status quo interest groups blocking such rule adoption. For nations whose topography is such that there are some geographic areas that face less extreme heat and flooding risk, these might be the most promising places to build new cities. If the fixed costs of creating the first stage of urban infrastructure can be reduced, then these experiments will not be that costly to run. If the cities take root, then the second generation of infrastructure can be built to a higher quality.

5 GENERAL EQUILIBRIUM EFFECTS INDUCED BY RAPID URBANIZATION

Severe climate shocks to the LDC countryside may create large urban migration flows that shift out the aggregate supply of labor in cities and increase aggregate housing demand. If large enough, these shocks have general equilibrium effects and thus affect the well being of incumbents in these cities.

Consider a LDC city that specializes in low skill manufacturing. If the manufacturing wages in this city are quite high, then incumbent firms will be delighted as new migrants move to the city. Such an influx of migrants will lower local wages and incumbent workers will experience an income loss. Rents will rise in areas experiencing an in-migration. These general equilibrium effects hinge on the underlying elasticities and these are crucial for the political economy discussion of urban migration that we present below.

The effects of migrants on local labor and real estate markets is a hotly debated US issue but it has not been explored in enough depth in the LDC context. The Mariel Boatlift represents a famous case study of how a city is affected by rapid migration (Card, 1990). In the standard Econ 101 short run perfectly competitive model, a rapid increase in the supply of low skill workers lowers equilibrium wages for low skill workers and raises rents (Saiz, 2003). Borjas et al. (1997) extend this to a two sector general equilibrium model. As Miami's wages went down and rents rose (due to the Cuban immigration), some Miami incumbents started to move out and moved to places such as Atlanta. In the resulting long run spatial equilibrium, wages and rents adjust so that the footloose are indifferent between living in the treated city "Miami" or the non-treated city (Atlanta).

Whether the Mariel Boatlift offers a preview for likely general equilibrium effects in the developing world hinges on several factors. Ades and Glaeser (1995) document that in the developing world a large percentage of urbanites live in the capital city. This effect is even larger if the nation is authoritarian and is closed to international trade. For LDCs that fall into this category, it is likely that rural migrants will also seek to move to the capital city.

A growing development economics literature has studied urban slums. In these areas, people squat for years on land often owned but not policed or serviced by the state (Fields, 2005). In such areas, rising population density can contribute to infectious disease risk and fears of violence. Brueckner (2013) has studied the housing conditions in Indonesia's slums. Residents in these areas live in low quality housing such that natural disasters are more likely to cause more death risk, destruction and infectious disease.

An emerging literature has been examining urban slum housing (see Brueckner and Selod, 2009; Brueckner, 2013). Empirical research tends to survey such properties to collect data on whether the home has a secure roof, toilet pipes and access to electricity. Such descriptive research could be augmented to study whether such housing, both due to its physical location and its quality, is less resilient in the face of natural disasters and extreme weather conditions than housing in the formal sector. Such research would be highly relevant for studying whether climate change will exacerbate quality of life inequality between the poor and the urban rich. This could occur if the urban rich live in higher quality structures that are more resilient to extreme heat and natural disasters (because of better roofs and better sanitation investments).

As rural people move away from their villages to the cities, land resources per-capita in the countryside increase (Young, 2005). This means that rural incomes will rise and thus the LDC urbanization trend could help the remaining rural people to better adapt to the emerging climate conditions. Research from Brazil has documented that the preservation of countryside natural capital contributes to lowering disease risk (Bauch et al., 2015). The electrification of the countryside and the increased access to Internet Technology raises the possibility that rural quality of life improvements could help to slow rapid climate change induced urbanization (Wolfram et al., 2012). If improvements in information technology could allow countryside people to earn income while not working in farming, then this will provide some risk diversification for countryside residents.

5.1 URBAN POLITICAL ECONOMY ISSUES RELATED TO CLIMATE CHANGE ADAPTATION

As LDC cities grow in population size, local leaders will face key decisions. Do they provide key infrastructure such as electricity, housing and sanitation for the rural entrants or do they try to discourage migration to their city by making living conditions miserable? The urban poor tend to live in the riskiest parts of the city, in high density areas. While high population density living is considered "green" in rich nations as it yields a low carbon footprint (think of high rise Hong Kong and Manhattan), in developing countries high density is associated with infectious disease risk from water pollution and air pollution exposure.

Poor people have the least ability to use market products such as air conditioning to self protect. An open question is whether local officials recognize this point, step up and provide public goods for this group. In US cities, cooling centers have been opened to shelter the urban poor on the hottest days. As developing countries grow richer, will they devote more of their expenditure to "pro-poor" public goods that helps to shield the poor from increased risks?

Research from Brazil highlights that local urban officials often do not engage in "pro-poor" policies. Feler and Henderson (2011) provide a cautionary tale from Brazil. Using a cross-section of data across cities, they find that cities are intentionally under-providing water connections to urban migrants. One explanation for this fact is to act as a barrier to entry. A city that is accommodating to new migrants will likely receive even more migrants. By denying such water connections, these leaders are trying to discourage rural to urban migration. Whether this Brazilian case is typical across LDC nations is an important question for future research. Work by Besley and Burgess (2001) finds that in India government officials are more responsive in providing public goods in geographic areas featuring a more literate public. They argue that the media plays a key role here in publicizing elected officials' actions.

If a local mayor seeks to upgrade local public goods, this raises the question of how to finance these investments. If international capital markets were integrated, cities with a good reputation for paying back past debts could borrow on such markets by issuing municipal bonds. In many developing countries, the federal government does not allow them to issue such debts both because the center wants to keep control over the localities and because the center recognizes that it will held responsible if a city borrows and then due to corruption defaults on such a debt. Cutler and Miller (2006) document an optimistic US historical case study. They show that in the 1930s US cities were able to sharply reduce their water borne disease death risk by issuing bonds to build such treatment facilities. In the absence of such financing mechanisms, there are likely to be many climate adaptation friendly infrastructure projects that are not implemented because of financing constraints. Examples include water treatment facilities, flood water disposal, and coastal flood protection.

Standard Ricardian logic predicts that any public investment such as reducing water disease risk will be capitalized into local land values. This suggests that land owners in cities are an interest group with strong incentives to encourage leaders to engage in efficient public goods provision. If LDC cities can introduce a property tax then this would provide a strong incentive for mayors to invest in such climate adaptation friendly public goods, because the mayor would have a larger revenue from the tax base.

A second pathway to incentivize urban leaders in democracies in LDCs is to provide report cards on their respective performance (Ferraz and Finan, 2008). For those LDC nations featuring multiple cities, a type of beneficial Tiebout competition allows urbanites to "vote with their feet" such that they move away from cities whose taxes are high relative to the public services they provide. Such potential for population loss provides an incentive for local officials to deliver services. We recognize that this accountability movement will be less successful in dictatorships in the developing world. The political economy of the incentives of local officials in dictatorships to protect the urban poor remains an open question.

5.2 THE ADAPTATION BENEFITS OF LDC URBANIZATION

Urban economists posit that urbanization raises individual income through encouraging human capital accumulation, learning and specialization (Glaeser, 1998). The human capital externality literature has emphasized the key role that knowledge spillovers play in economic growth and in raising individual's income (Rauch, 1993). Education and urbanization are strong complements. In cities, women have greater labor market opportunities and this encourages them to have fewer children and to invest more in each of their children (Becker and Lewis, 1973). This Becker quality/quantity tradeoff has implications for climate adaptation as more educated young people will be more nimble in adapting to new emerging risks.

If urbanization has a causal effect on raising one's income, then a household has greater capacity to protect itself from climate risks. A richer household has the income to purchase an air conditioner (Davis and Gertler, 2015; Barreca et al., 2016), cell phone (Aker, 2010; Jensen, 2007), high quality housing, better food, proper transportation and access to better medical care. Together these market inputs act to protect urbanites from a variety of challenges. Access to electricity plays a key role in all of these activities. In LDCs, the urban sector has better access to cheaper reliable electricity. This higher quality of consumption of housing and access to basic durables reduces the population's fatality risk in the face of increased quantity and severity of natural disasters (see Kahn, 2005). Kellenberg and Mobarak (2008, 2011) argue that in the poorest nations that urbanization and slow urban economic development combine to expose the population to higher death count risk relative to if the population were uniformly distributed.

Over time, the purchasing power of urban incomes increases as world quality adjusted prices for durables decline. What is the minimum income a household needs in each nation to have access to a cell phone, air conditioning, medical care, safe housing and refrigeration? Such an expenditure function approach would allow researchers to quantify the ability of a given nation's diverse population to adapt to new risks using private self protection.

As LDC cities grow richer, it is likely to be the case that the urban populace demands greater safety and environmental regulation. The Environmental Kuznets Curve argument is predicated on a rising demand for regulation as economic development takes place (Dasgupta et al., 2002). The so called "j-Curve" for regulation optimistically posits that as the urban middle class grows, this group becomes an active interest group seeking improved local public goods (Selden and Song, 1995). In the case of adapting to climate change, the urban middle class in LDCs will increasingly support policies that provide public goods (i.e. sea walls) that protect the local populace from emerging threats. The hypothesis that the growing LDC middle class supports increased investment in defensive public goods is a promising future research topic.

5.3 THE PRODUCTIVITY OF LDC URBAN FIRMS IN A HOTTER WORLD

The previous section argued that LDC urbanization will accelerate per-capita income growth and human capital attainment. How will climate change affect this gradient? The answer hinges on whether climate related events sharply lower urban firm productivity.

A recent literature has studied how indicators such as firm level output and total factor productivity over the course of a year vary with local climate conditions (Heal and Park, 2016).

A fruitful area for future research could merge micro data on LDC urban firm productivity with local measurements of temperature and rainfall. Such data could be used to estimate firm level production functions augmented by climate variables. These regressions yield an estimate of the marginal productivity costs of extreme climate.

A central difference between agriculture and urban production is the possibility of adopting air conditioning. In an economy featuring heterogeneous firms, the most productive firms will be the most likely to adopt this costly technology. Zivin and Kahn (2016) present a model of the adoption of air conditioning by urban firms. The adoption of air conditioning is a costly investment. Zivin and Kahn (2016) present a model of heterogeneous firms within an industry. In their model, firms all produce the same output but differ with respect to their productivity. This source of productivity is taken as exogenous. Extreme heat lowers the productivity of workers. Each firm calculates its profit from having air conditioning (and bearing the fixed cost and operating cost of the air conditioner) versus its profit from not having air conditioning. In their model, there is a cutoff firm in the productivity distribution such that all firms, who are more productive than that firm, adopt the air conditioning. This result immediately suggests that the most productive firms will be more likely to be insulated from climate change. As outdoor conditions grow hotter or if the price of air conditioning declines, the less productive firms will become more likely to adopt air conditioning. Zivin and Kahn solve for the macro aggregate industrial output that is insulated from the heat due to air conditioning. Their model predicts that the most productive firms will grow as extreme heat takes place and they will hire more workers who will be air conditioned.

Extreme heat in cities could exacerbate income inequality as the less productive workers work for the less productive firms who choose not to provide air conditioning. This hypothesis could be tested if matched worker/firm level data in LDC nations could be collected. Such a data set would include worker attributes such as age, education, gender and standardized test scores and firm attributes such as the firm's industrial sector, price of output, inputs used in production, the firm's physical location and its energy used and ideally indicators of air conditioning. Such a data set could be used to test whether high skilled workers are working at air conditioned firms and whether in hot years these firms perform better based on output per worker compared to firms in the same industry that do not have air conditioning.

5.4 WILL LDC URBAN GROWTH SIGNIFICANTLY EXACERBATE THE GLOBAL GHG EXTERNALITY CHALLENGE?

Adaptation is easier if global GHG emissions are lower. In the near term, the developing world will contribute a growing share of the world's greenhouse gas emissions (Auffhammer and Carson, 2008). A simple decomposition exercise represents total GHG emissions as equal to population $*$ GNP $*$ Emissions per dollar of GNP. Given this formula, how much will LDC urbanization and economic growth contribute to the overall GHG production externality? Urban growth should slow down overall population growth. A standard Beckerian model of the optimal number of children to have incorporates the full costs and benefits of children. In cities, the value of alternative uses of their time over work in the household sector is higher. Urbanization and education go hand in hand and more educated (men and) women can earn higher urban wages (Becker and Lewis, 1973). This higher value of household time creates an incentive for women to substitute from quantity of children to quality of children as urban women have fewer children and invest more time in each one. In recent years, nations such as Vietnam have had a dramatic decrease in fertility rates. While urbanization slows down LDC population growth, it accelerates per-capita income growth. Richer people consume more private goods that run on electricity and fossil fuels. The prime examples are private vehicles, and household durables such as air conditioning and refrigerators. If power is generated by coal then this consumption will be socially costly. If the developing world adopts natural gas, nuclear and renewables, then the resulting GHG externality associated with the rise of the "American Dream" in the developing world will be lower. Glaeser and Kahn (2010) present an empirical approach for measuring the household carbon footprint by city. This approach has been used to rank Chinese cities with respect to their carbon footprint (Zheng et al., 2010).

Endogenous technological change can reduce emissions per dollar of GNP. New innovations such as electric vehicles charged by solar panels raises the possibility that developing nations can have access to personal services without the resulting carbon externality. Of course there are many sources of uncertainty in the engineering prospects for these nascent technologies. The interesting economic question here is whether the growth of LDCs as urban centers of consumption (think of the product demands of China's large upper middle class) acts as a "Big Push" encouraging further R&D in green technology. Put simply, if China's growing middle class demands electric vehicles then this creates a huge market for firms that can produce this variety (Acemoglu and Linn, 2004).

In a growing world economy, the rising stock of human capital raises the possibility of significant progress in the development of green technology such as electric vehicles and renewable power generation equipment (Freeman and Huang, 2015). A countervailing trend has been the rise of technological progress in the fossil fuel sector such as the fracking revolution. This race between progress in green versus brown technology will play a crucial role in determining whether the LDC rural to urban (and the resulting growth in per-capita income) transition accelerates global GHG emissions production.

5.5 RESEARCH NEEDS

Throughout this survey we have emphasized the importance of using micro longitudinal data at the individual, land parcel and firm level to trace out the effects of climate change on diverse economic agents. Such data will allow researchers to test for heterogeneous treatment effects of climate impacts. By simultaneously tracing out how the dynamics of the land parcel and the pathway followed by workers at that land parcel, research teams can study how people and places are affected by climate shocks. For example, an optimist would posit that after a permanent climate shock that the land will quickly transition to its highest value use and the people who were employed there will easily transition to their next best alternative. A research team with longitudinal data on parcels and people can directly test this hypothesis and thus will be able to measure who bears the economic incidence of climate change.

Empirical research progress in climate adaptation research will mainly come from exploiting natural experiments. As natural disasters and heat waves inevitably occur, this exogenous variation will allow the researcher to trace out the short run and medium term effects. Field experiment research designs can be introduced to see if certain low cost interventions attenuate the negative effects of a given shock. For example, if climate change increases the severity of coastal hurricanes, then a field experiment that randomly assigns a subsidy for more sturdy roofs on homes will yield a test of whether housing structure insulates a poor household from such shocks.

Much of the new climate economic research estimates reduced form models using a single equation to link "cause and effect". This research plays a crucial role in teaching us new facts. A prime example is Barreca et al. (2016). This US study documents the reduced mortality effects of extreme heat over time perhaps due to the diffusion of air conditioning.

A gap we see in the literature is a paucity of structural modeling. Optimizing households and firms choose where to locate and how to produce. This raises classic self selection issues of sectoral choice based on evolving comparative advantage. Costinot et al. (2016) provide such an analysis for the agricultural sector. This approach would explicitly allow researchers to study who “is the marginal economic agent” induced to change sectors because of a given shock.

6 CONCLUSION

Around the world, the share of people whose income is below the poverty line is declining over time. But per-capita income is not a sufficient statistic for quality of life. Climate change could lower the standard of living in LDC nations even if per-capita GDP is rising. The poor who live in poor nations are the most likely to bear the greatest costs caused by climate change. This chapter has investigated many facets of the anticipated challenges posed by weather shocks and natural disasters.

By adopting a microeconomic perspective, this paper has focused on the distributional impacts likely to be caused by emerging climate change. Rural people may face subsistence consumption risk, dislocation and higher levels of violence. Poor urbanites living in informal areas could face an influx of desperate rural migrants who through market competition will raise rents and lower wages for incumbent urbanites. We have emphasized the importance of testing for heterogeneous responses and measuring the economic incidence of coping with new ambiguous risks.

The value of this research agenda is that it complements an emerging macro literature that makes cross-country comparison in the standard of living (Jones and Klenow, 2016; Stiglitz et al., 2009). This “well being” literature has not incorporated the long run looming threat of climate change. We have explicitly examined how self interested decision makers are likely to cope with the new challenges they face. This chapter’s proposed research agenda will lead to a better understanding of how the standard of living of the poor will evolve in LDCs dealing with climate change.

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