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Abstract

In this review, we summarise the literature on weather and climate adaptation in developing countries. First, we document the effects of climate change and extreme events on economic outcomes. Climate change and weather shocks impact households, firms, and countries negatively across a range of important outcomes such as income and mortality. These effects are usually quite large and can transmit across space via supply relationships or migration, and persist across time, including in some instances for decades. Next, we review the evidence on the effectiveness and efficiency of various adaptation approaches. We discuss adaptation through financial products, new technologies, mobility, and government policies. The literature indicates that while households, farmers, and firms undertake a variety of adaptation measures, these are seldom able to mitigate the impacts of climate completely, indicating that policies to facilitate adaptation will likely have large welfare gains. As developing countries begin to ramp up efforts to facilitate adaptation and receive international climate financing for adaptation, understanding how these can be best allocated to high-impact regions and policies should form a crucial set of questions for future work.

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Summary

Developing countries face the joint challenge of reducing poverty and adapting to a changing climate, while in some cases also needing to reduce their greenhouse gas emissions. Currently, 60% of the world's population lives in a place where a hotter year causes lower GDP growth, and by 2100, 75% will (Acevedo et al. 2017). Therefore, even if the ambitious global target of limiting warming to two or below degrees is reached, there will be a substantial need to allocate resources towards adaptation, and balance the need to increase resilience to climate change with economic growth.

Developing countries are most vulnerable to climate change for a range of reasons. These include a greater impact of temperature on output (Acevedo et al. 2017, Burke et al. 2015), long coastlines which increase vulnerability to certain extreme events (Balboni 2021), and lower incomes, which can impact resilience and the ability to undertake adaptive investments. Furthermore, on average, mean temperatures are higher in developing countries, implying that further warming may increase this vulnerability. Finally, developing countries have lower access to social safety nets, further increasing households' vulnerability in the face of climate shocks (Hanna and Oliva 2016).

This review summarises the literature on climate adaptation in developing countries, focusing on three aspects in particular. The first is the literature on quantifying vulnerabilities to weather and climate, which focuses on the cost of weather and climate shocks on important economic outcomes, like income, conflict, human capital formation, productivity, and mortality. The second is the literature on measuring adaptation by individual actions, such as technology adoption, migration and job-switching, as well as government policies including safety nets. The third summarises the recent literature on spatial linkages and general equilibrium approaches to climate change adaptation. The effects of climate shocks may be transmitted across regions via general equilibrium adjustments along a range of margins which have been investigated in recent empirical studies such as migration, or through production networks between firms. Accounting for these responses has been found to have quantitatively meaningful implications for estimates of climate change damages and our understanding of adaptation requirements and mechanisms.

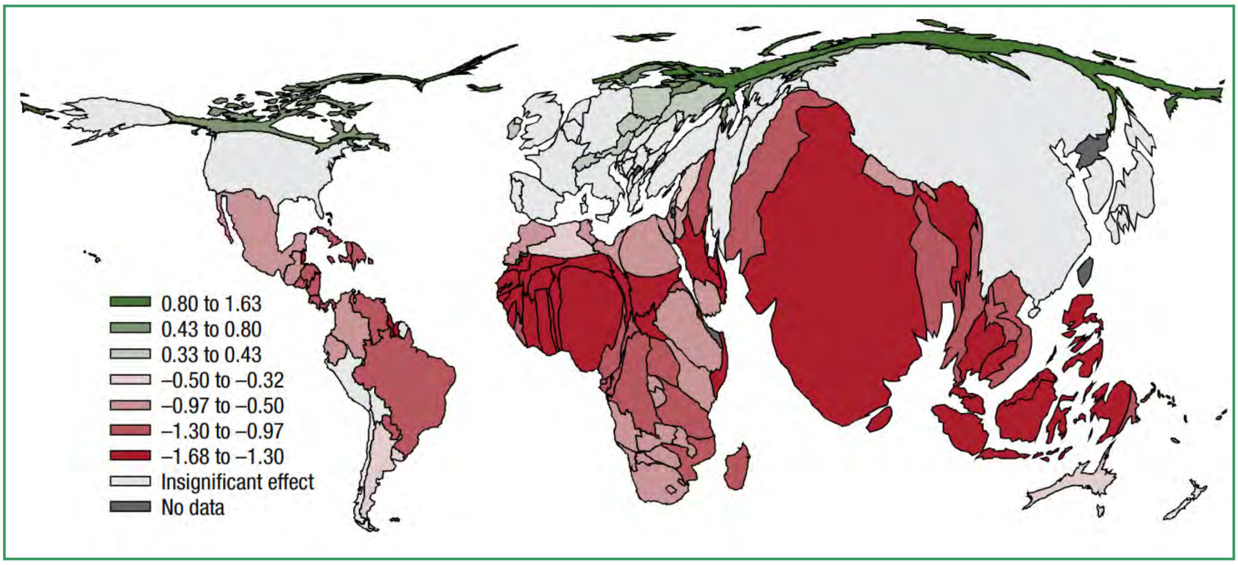
There are four aspects of the literature that are noteworthy. First, climate change and weather shocks impact households, firms, and countries negatively across a range of first-order outcomes such as income, conflict, human capital formation, productivity, and mortality. Second, these effects are usually quite large and can transmit across space via supply relationships or migration, and persist across time, including in some instances for decades. Third, while households, farmers, and firms undertake a variety of adaptation measures, these are seldom able to mitigate the impacts of climate completely, indicating that policies to facilitate adaptation will likely have large welfare gains. Fourth, while socio-economic policies can provide safety nets and minimise frictions that catalyse adaptation, political economy concerns may also shift the focus away from climate resilience. As developing countries begin to ramp up efforts to facilitate adaptation and receive international climate financing for adaptation, understanding how these can be best allocated to high-impact regions and policies should form a crucial set of questions for future work.

I Introduction

Developing countries face the joint challenge of reducing poverty and adapting to a changing climate, while in some cases also needing to reduce their greenhouse gas emissions. From 1990 to 2015, the global extreme-poverty rate (as measured by the $2.14 per day benchmark) fell steadily, but in recent years this progress has slowed, and in some instances reversed (World Bank 2020). Currently, 60% of the world's population lives in a place where a hotter year causes lower GDP growth, and by 2100, 75% will (Acevedo et al. 2017). Therefore, even if the ambitious global target of limiting warming to two or below degrees is reached, there will be a substantial need to allocate resources towards adaptation, and balance the need to increase resilience to climate change with economic growth.

Developing countries are most vulnerable to climate change for a range of reasons. These include a greater impact of temperature on output (Acevedo et al. 2017, Burke et al. 2015), long coastlines which increase vulnerability to certain extreme events (Balboni 2021), and lower incomes, which can impact resilience and the ability to undertake adaptive investments. Furthermore, on average, mean temperatures are higher in developing countries, implying that further warming may increase this vulnerability. Finally, developing countries have lower access to social safety nets, further increasing households' vulnerability in the face of climate shocks (Hanna and Oliva 2016).

Figure 1 Impact of one degree Celsius hotter temperature on GDP per capita (Acevedo et al. 2018)

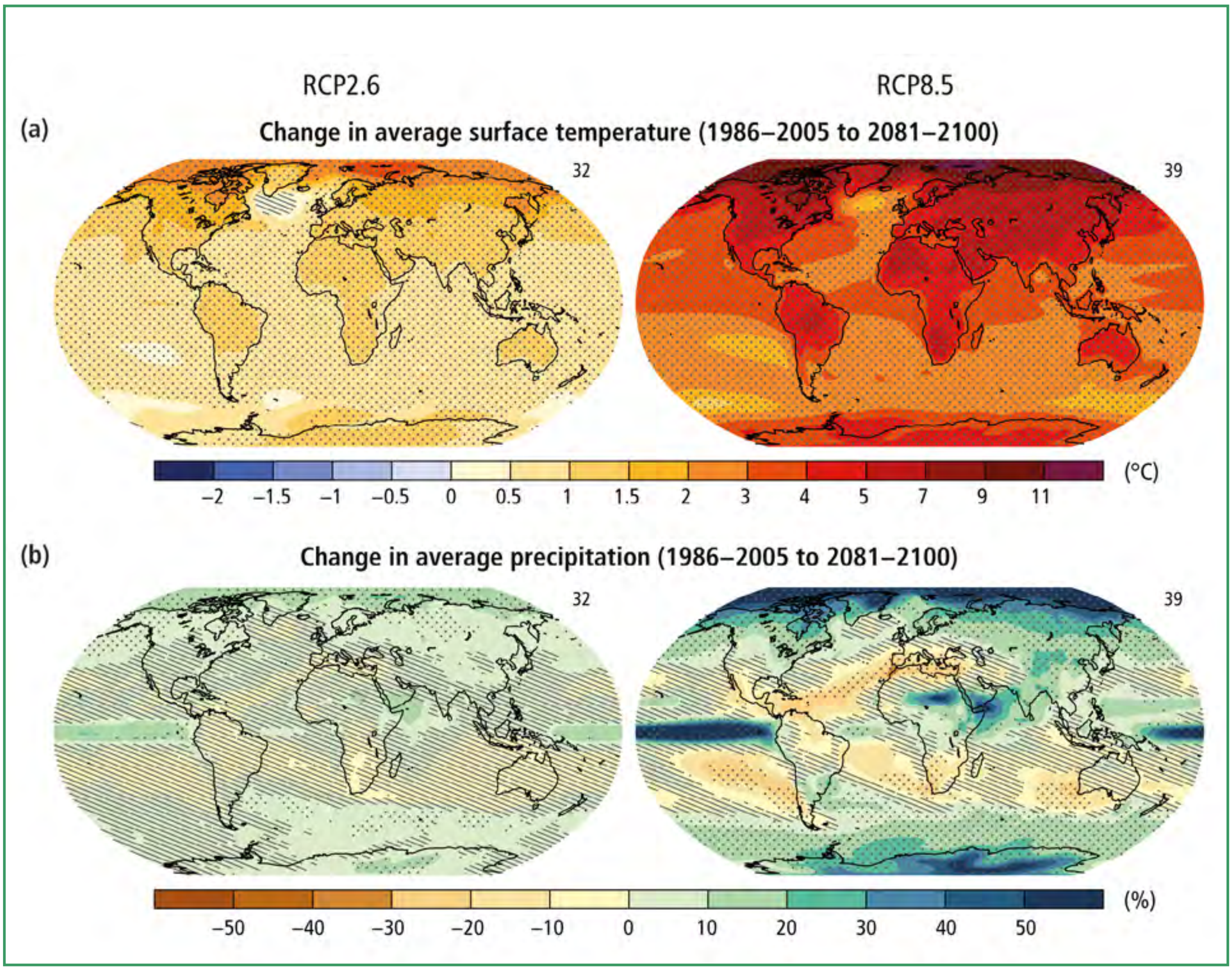


Source: Acevedo et al. (2018).

Note: The map depicts the effect of a 1°C increase in temperature on real per capita output at the country level, with countries rescaled in proportion to their population.

This review summarises the literature on climate adaptation in developing countries, focusing on three aspects in particular. The first is the literature on quantifying vulnerabilities to weather and climate, which focuses on the cost of weather and climate shocks on important economic outcomes. The second is the literature on measuring adaptation by individual actions as well as government policies. The third summarises the recent literature on spatial linkages and general equilibrium approaches to climate change adaptation.

Figure 2 Projected climate change (IPCC 2014)



Notes: Multi-model mean projections (i.e. the average of the model projections available) for the 2081–2100 period under the stringent mitigation (RCP2.6, left) and very high emissions (RCP8.5, right) scenarios for (a) change in annual mean surface temperature and (b) change in annual mean precipitation, in percentages (IPCC 2014).

II Measuring the impacts of climate change and adaptation

This section presents an overview of different approaches to measuring climate change adaptation, as well as their advantages and disadvantages. Two things are worth noting before we undertake a detailed description of these methods. First, some of the studies cited used data from developed countries, but they are relevant to this review because of their methodological contribution, and later in the review we highlight where these methods might diverge when using data on developing countries. Second, "climate" and "weather" by definition include a large number of phenomena that are relevant for economic outcomes in developing countries, including (but not limited to) temperature, rainfall patterns, and a multitude of extreme events such as hurricanes and floods. Most studies consider a subset of these (e.g. either temperature and rainfall or hurricanes) when estimating impacts.

IIA Cross-sectional studies

Climate change manifests through rising temperatures, unpredictable rainfall patterns, and increasingly frequent natural disasters. The earliest studies estimating the economic impacts of climate change relied on agronomy models of the impact of heat exposure on plants to quantify how higher temperatures would impact agricultural yields, which have over time developed into models that allow for several important agronomic factors (Rosenzweig et al. 2014).

To understand how agricultural profits (rather than yields) would respond to climate change, Mendelsohn et al. (1994) used cross-sectional data on agricultural land values in the US and regressed them on 30-year average temperature and rainfall variables (using linear and quadratic terms for each of these variables to allow for nonlinear effects of climate), as well as control variables for soil, market access, and related confounders. The rationale behind using land prices was that these variables should capitalise the long-term value of climate in a location (which could be negative), and the advantage of using long-term weather averages was that it allowed for adaptation and estimated the effects of climate change net of adaptation. Using the estimated marginal values of temperature and precipitation, they predict land values in each county using the current climate, and then using the future climate, allowing them to compute the impacts of climate change. The results from this study predicted small impacts of climate change on US agriculture.

Follow-up studies focused on other countries, including developing countries, and additionally directly estimated the returns to adaptation, such as irrigation (Seo et al. 2005, Kurukulasuriya et al. 2011), finding large negative impacts of climate change on agricultural profits in developing countries. However, a drawback of these studies is that the primary right-hand side variables are cross-sectional (i.e. 30-year average temperature and precipitation), meaning omitted variable bias may be a concern when interpreting these estimates – climate may be correlated with infrastructure quality or other variables which are omitted from the regression specification. If so, the estimated impact of climate may be biased.

IIB Identification via weather shocks

Given the identification concerns with cross-sectional approaches, follow-up work relied on using weather shocks, rather than long-term climate, when estimating the impacts of climate change. These papers (Deschênes and Greenstone 2007, 2012, Fisher et al. 2012, Graff et al. 2014) used panel data on agricultural profits and weather variables (temperature and precipitation) to estimate how weather shocks, usually measured as annual or seasonal deviations from long-term climate, impacted agricultural profits in the US. Using these weather variables, Deschênes and Greenstone (2012) find predicted losses of about $4 billion for US agriculture by the end of the century when extrapolating to future predicted climate scenarios (they use values of agricultural profits predicted using the impacts of weather shocks, and the projected climate for each county). Similar to the cross-sectional approaches, these studies usually extrapolate the estimated marginal effects of climate or weather to a future climate scenario to compute how climate change would affect the outcome of interest in the future.

A significant advantage of this approach is that the use of panel data methods mitigates omitted variable bias. For this reason, this approach has been subsequently influential and currently is the most used approach in estimating the impacts of weather shocks and climate. A potential disadvantage is uncertainty regarding extrapolating the impact of say, one hotter year by two degrees Celsius, to a world that is permanently warmer by two degrees. The impact of a weather shock may be an overestimate relative to a changed climate if some adaptations may be available in the longer term that are not available in the short run (e.g. switching crop varieties, or innovation of more heat-resistant varieties in the even longer term). In contrast, if short-run adaptations are possible that are infeasible in the longer term, e.g. excessive pumping of groundwater to irrigate and mitigate the impact of a hotter year, weather shocks may provide an underestimate of climate change (see Lemoine 2018 for a detailed treatment of these issues).

More recently, work in developing countries has estimated the impacts of weather shocks on a diverse set of economic outcomes, ranging from agricultural profits, worker and firm productivity, and economic growth. Several of these studies also consider adaptation, which we discuss in the next section. Dell et al.

(2012) show that higher temperatures substantially reduce economic growth in poor countries, adversely impacting both agricultural and industrial output. Guiteras (2009) finds that weather shocks reduce crop yields by about 5% to 9% in India, with longer-term damages estimated to be 25% of crop yields in the absence of adaptation. Somanathan et al. (2021) use plant-level Annual Survey of Industries (ASI) data on manufacturing firms in India and find reductions of 2% of annual output per one degree Celsius of hotter temperatures. Zheng et al. (2018) estimate an inverted U-shaped relationship between temperature and TFP in China, with both labour- and capital-intensive firms exhibiting sensitivity to high temperatures. Other work has focused on how weather shocks impact labour markets, such as the intersectoral allocation of labour (Colmer 2021, Santangelo 2019). The negative impacts of weather are present not only when considering annual level shocks, but also daily variation. Using data for blue-collar (garment factory) workers in India, Adhvaryu et al. (2020) find that daily temperatures exceeding about 85 degrees Fahrenheit substantially lower production-line level productivity that day, an effect that is not driven by selection into the type of workers that attend work on hotter days.

In addition, recent work has found the effects of hotter years on human capital formation in developing countries. Garg et al. (2020) show that high temperatures reduce maths and reading test scores among school-age children, an effect that is higher during agricultural growing seasons, when hotter temperatures also reduce crop yields. Even beyond contemporaneous effects of heat on education, Fishman et al. (2019) find that in-utero exposure to an additional degree celsius of temperature has long-term effects on education and earning. Shah and Steinberg (2017), in contrast, find that contemporaneous positive rainfall shocks increase child labour for children aged five and higher, and lower human capital investment, as they increase the opportunity cost of spending time in school for children.

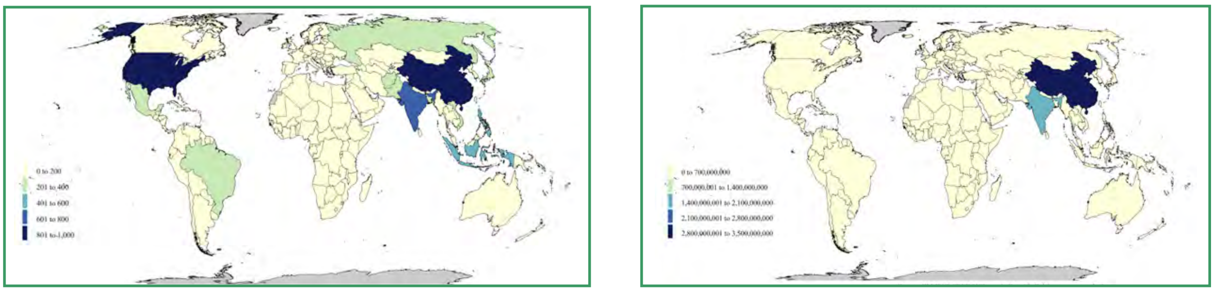
Related work has also examined the impacts of weather shocks on infant mortality and mortality more broadly. For instance, Burgess et al. (2017) find that hotter years in India increase mortality within a year of their occurrence, an effect that is present in rural households. Furthermore, hotter and drier years also reduce agricultural output as well as wages. Banerjee and Maharaj (2020) find negative impacts of hotter years on infant mortality in India and also test whether workfare programmes and community health programmes can mitigate this relationship (described in more detail in the next section). Geruso and Spears (2018) use Demographic and Health Survey (DHS) data from 53 developing countries, and similarly find negative impacts of hotter years on infant mortality. In terms of magnitude, their estimated effect sizes are large, comparable to similar estimates in the US, prior to air conditioning adoption, between 1930 and 1959. Furthermore, some papers test whether exposure to early-life weather shocks negatively impacts later-life outcomes. Maccini and Yang (2009) find that exposure to higher early-life rainfall in the year of birth leads to improved health, schooling, and socioeconomic status for women in the Philippines, with no effect of higher rainfall in-utero. Shah and Steinberg (2017) find that positive rainfall shocks in-utero and early in life increase the likelihood of a child being in school in India.

Other important economic outcomes in developing countries impacted by warming and rainfall shocks include crime as well as civil conflict (see Burke et al. (2015) for a comprehensive review). Burke et al. (2015) evaluate data from 60 studies using 45 different types of conflict data and find that higher temperatures and lower rainfall increase conflict across the developing world. Blakeslee and Fishman (2018) use data on crime and weather in India between 1971 and 2000 and find that hotter years and drought years increase all types of crime. Such shocks can also increase gender-based violence such as dowry deaths in India (Sekhri and Storeygard 2014) and witch killings in Tanzania (Miguel 2005). While lower income or resources leading to conflict is one likely mechanism that is often found to be important in explaining the effects of these shocks (McGuirk and Nunn 2021), it is often not sufficient to explain the entire impact, indicating that the complete set of mechanisms via which weather shocks impact conflict and crime are not yet fully understood.

In addition to estimating the impacts of weather on final economic outcomes such as productivity, profits, and crop yields, this literature has also looked at how different natural disasters impact economic outcomes. Developing countries have among the highest occurrence of natural disasters, but more importantly, have the highest number of people affected by them – see Figure 3 reproduced using EMDAT data (Guha-Sapir et al. 2023). Hsiang and Jina (2014) find that cyclones reduce economic growth for both rich and poor countries, with persistently negative impacts on economic growth. Using panel data on Indian firms, Pelli et al. (2023) find that hurricanes impact firms' exit rates and sales, and these effects are larger for less productive firms. They also find evidence that after the hurricane, firms respond by abandoning production in industries with lower comparative advantage. Elliot et al. (2015) use nightlights data to estimate how typhoons impact short-run local economic activity in China - they find that a typhoon estimated to destroy 50% of the property reduces local economic activity by 20% in the same year, with total net economic losses from typhoons estimated to be about $28 billion between 1992-2010.

Baez and Santos (2007) find that children in regions that were affected by Hurricane Mitch in Nicaragua had worse health outcomes as well as a lower probability of seeking healthcare conditional on being ill. Caruso (2017) combines census data for Latin America and the Caribbean with data on natural disasters and finds that disasters negatively impact educational attainment for affected children, with impacts varying by the age of exposure to disaster, the type of natural disaster, as well as the place and time of exposure. The results raise important questions about the ability to extrapolate impacts from one country to another and show the persistent negative impacts disasters can have on impacted populations. The paper also finds a U-shaped relationship between GDP per capita and impacts on educational attainment.

Figure 3 Global occurrences of natural disasters and impacted populations (EMDAT Database)



Panel A: Global Occurrences of natural disasters by country between 1980 - 2023

Panel B: Total population affected by natural disasters by country between 1980 - 2023

Source: Guha-Sapir et al. (2023).

IIC Recent methodological developments

This section reviews some recent methodological innovations in estimating climate impacts and adaptation. The first such approach is using long-run (for instance, decadal) changes in temperature and precipitation, which avoid some concerns regarding the lack of adaptation when estimating the impact of short-run weather shocks. Burke and Emerick (2016) estimate the impact of decadal changes in temperature and precipitation on maize and soya yields in the US and find large negative impacts in counties with greater decadal warming. They also find limited to no adaptation, indicating that losses from climate change are likely to be large for these crops. Liu et al. (2023) use long differences to test how decadal changes in temperature impact the sectoral allocation of labour and urbanisation in India. They find that a one degree Celsius increase in temperature in an average district in India increases the share of the labour force in agriculture by 17% and decreases the share of the labour force in non-agriculture by 8%, with no impact on urbanisation (although Henderson et al. (2017) find heterogeneity in the effects of climate shocks on urbanisation with positive effects when the cities are manufacturing centres). This approach incorporates the role of adaptation partially by estimating the impact of longer-run weather patterns but may have the drawback of limited support over which impacts can be estimated.

The second approach is to use the differences in the impacts between trends in warming and short-run temperature shocks to quantify the extent of adaptation. This is the approach taken by Bento et al. (2020), who use it to quantify the impact of climate change on atmospheric ozone concentration to detect adaptation (an absence of adaptation would imply similar ozone concentrations for given temperature changes). The third approach is to use machine learning to identify which weather variables are quantitatively important in determining economic outcomes such as crop yields, rather than relying on particular functional forms or weather variables. For instance, Hultgren et al. (2022) use machine learning approaches to estimate how weather shocks impact crop yields for six crops globally over time, finding considerable negative effects – they find that a one degree rise in global mean temperature reduces crop yields by about 4.5%, with limited adaptation. This approach has the distinct advantage that it does not rely on the researcher to specify the correct functional form of the relationship between weather and economic outcomes.

IID Expectations

A different but related set of papers seek to understand how households' and firms' expectations regarding the weather and the climate impact their adaptation decisions. For instance, Shrader (2017) uses forecasts to understand their role in adaptation to El Nino/Southern Oscillation (ENSO) variation for albacore tuna harvesters in the North Pacific US. He finds that the benefits of forecasts in this setting are large, with the forecast allowing farmers to adapt to ENSO changes. Some caution is in order when extending these results to developing countries. In places where forecasts are trustworthy, they can facilitate adaptation to short-run weather. However, weather phenomena which are important for economic outcomes in developing countries may be more difficult to forecast – for instance, Rosenzweig and Udry (2013) show that the correlation between long-range monsoon forecasts and realised rainfall is very small in India, which implies that most farmers would rationally ignore this information. To capture the potential uncertainty caused by climate change in farmer decisions, Kala (2017) develops an empirical framework to test how farmers respond to the Knightian uncertainty possibly inherent in learning about a changing climate, i.e. in the short and medium term, farmers may not even know whether the climate has changed. The paper finds that farmers' beliefs about monsoon onset are consistent with such learning behavior, but only in villages that have experienced greater changes to the rainfall distribution in recent decades.

Other work has also looked at how expectations regarding climate change – namely climate change forecasts themselves – can be priced into land markets. Severen et al. (2018) find that climate change forecasts are partially priced into land markets, and land values are more strongly related to future climate predictions in counties with higher beliefs in climate change in the US. This study provides an innovative test of how climate change may be priced into vulnerable assets, but certain features of asset markets in developing countries imply that new methods or data may be required to apply these tests in developing countries. These features include the relative thinness of agricultural land markets, as well as transaction costs due to undigitised land records (Beg 2022).

In conclusion, it is worth noting that the bulk of the literature finds large negative impacts of warming and lower rainfall in developing countries with limited adaptation. This indicates that policy interventions to facilitate adaptation will likely be required. In the next section, we review the literature on adaptation responses.

III Adaptation responses

The early work on adaptation to climate shocks in developing countries focuses on agricultural households' management of risk from uncertain or abnormal rainfall through formal and informal financial markets (see Besley 1995 for a review of this work), labour supply decisions (Fafchamps 1993, Kochar 1999) and labour markets (Bardhan 1983), or migration networks and kinship (Rosenzweig and Stark 1989). This work finds that adaptation is costly in two ways:

1. Ex-ante mitigation responses from risk-averse farmers reduce productivity and profitability (Rosenzweig and Binswanger 1993, Rosenzweig and Wolpin 1993, Morduch 1995 for a review).

2. Ex-post adaptation is not complete, implying that they don't ensure recovery to pre-shock levels of income or consumption (Fafchamps et al. 1998).

The early papers theorise production functions, consumption decisions, and constraints to derive testable conditions on responses to weather uncertainty. These are corroborated empirically with fixed effects regressions using household panel data or regressions with controls from cross-sectional data. Recent work improves upon these empirical methodologies by employing randomised control trials (RCTs), quasi-random experiments from physical or policy variation, as well as short- and long-term shocks in weather (as described in the previous section) to evaluate a variety of adaptation and mitigation approaches.

This section summarises what we know about the effectiveness of different adaptation responses to climate events by elaborating on three modes of adaptation: (1) managing climate risk through financial products, (2) building resilience through technology adoption, innovation, and improved practices, and (3) the impacts of government policies.

IIIA Credit and insurance

The early approach to climate adaptation as a risk management problem naturally lends itself to evaluating the efficacy of financial products and markets. Here, we expand on the role of credit and insurance in building resilience to weather shocks and the importance of product design in addressing frictions to adaptation.

Karlan et al. (2014) show that, in Ghana, access to weather insurance overcomes the downside risk in agricultural settings and leads to increases in the scale of cropping and input investments, enhances revenues, and facilitates consumption smoothing relative to cash grants. The authors find positive effects on cropping investments from insurance, even in the absence of negative weather shocks, and show that farmers are able to crowd-in investments when their weather risks are insured. Lane (2023) further highlights that a novel financial product that provides both insurance and liquidity, by guaranteeing access to credit in the event of a flood, improved ex-ante investments in inputs and ex-post consumption outcomes for farmers in Bangladesh. Despite these positive effects of weather-indexed insurance, the take-up of such products remains low and highly price sensitive (Ahmed et al. 2020, Elabed and Carter 2014, Cole et al. 2013). Possible explanations for the low take-up of such insurance products include low trust, low liquidity to pay premiums, and limited salience of risk when farmers overweight recent events (McIntosh et al. 2019, Casaburi and Willis 2018, Karlan et al. 2014, Mobarak and Rosenzweig 2013).

Meanwhile, the literature considering non-agricultural firms has focused largely on liquidity constraints and credit interventions. De Mel et al. (2012) find that access to capital facilitates recovery and growth for firms exposed to natural disasters. Firms who randomly received access to cash grants recovered to their pre-disaster profit levels approximately two years before other affected firms who did not receive the grant. Annan et al. (2023) show that mobile money platforms enable firms to smooth over unexpected temperature and precipitation shocks in Ghana. They also show that if a weather forecast correctly predicts inclement weather on the previous day, then the harm from hot weather is substantially reduced for firms, indicating an ability to adapt. However, this financial avenue for climate adaptation is inhibited when firms face high levels of market competition. Evidence on how climate insurance shapes firms' decisions remains an underexplored area of research.

The benefits of credit in enabling firms to adapt can also be helpful for those in agriculture who are vulnerable to climate shocks. Macours et al. (2022) find that Nicaraguan households exposed to weather variability are able to offset the negative effects of drought shocks when provided with a bundle of conditional cash transfers with vocational skills training. The authors find that both interventions on their own were also able to improve resilience to droughts two years after the shock, although in different ways – CCT's enhanced investments in businesses and skills training intensified wage-work and urban migration. For natural disasters, evidence from Bangladesh suggests that forewarning vulnerable households through cash transfers announced in advance of an anticipated disaster allows them to prepare in advance, minimises losses and supports recovery (Pople et al. 2023).

Furthermore, Burgess et. al. (2017) find that bank expansion in rural India mitigates the mortality effects of heat by relaxing credit constraints.

IIIB Technology, practices, and innovation

New technologies and practices are a promising avenue for adaptation in both agricultural and non-agricultural settings. Improved seed varieties that build resilience to excessive rains have been shown to improve productivity and consumption outcomes, especially for more vulnerable groups (Dar et al. 2013). Emerick et al. (2016) show that the use of flood-resistant rice varieties expands cultivation, increases the takeup of modern cropping practices, and boosts the usage of inputs like fertilisers and credit in Eastern India. Eliminating the downside risk with this new technology not only impedes yield losses in the event of a flood but improves yields and farm revenues, even under normal conditions (similar to the results of reducing downside risk from insurance). Glennerster and Suri (2018) illustrate the positive effects of a short-duration, high-yielding rice variety that enables farmers to harvest during the wet season in Sierra Leone. The new rice variety improved yields, consumption, and health outcomes for children below the age of five. However, these positive effects were concentrated among farmers who also received high-touch training that addressed the germination sensitivity of the new seed, highlighting that the upfront costs of learning and adapting practices for new technologies could limit their returns and widespread adoption.

High costs of new technologies (Glennerster and Suri 2018), costly experimentation and learning (Foster and Rosenzweig 1995, Munshi 2004), heterogeneous returns to adoption (Dar et al. 2013, Suri 2011), or the absence of investments in innovations that are appropriate for lower-income countries (Moscona and Sastry 2022) could inhibit the adoption of new technologies that can potentially facilitate climate adaptation. Emerick and Dar (2021) find that bridging the information gap while building farmers' trust through farmer-field days, where farmers can interact with each other and observe the performance of a new seed, increases takeup by 40%. On the other hand, demonstrating the seed through progressive adopters chosen during participatory village meetings has no effect on adoption. That said, the effectiveness of this approach may be limited if other constraints, like liquidity, hold. For example, Glennerster and Suri (2018) find that providing high-yielding seed varieties for free led to a 97% take up as opposed to full-price offers (21% take up), showcasing the presence of liquidity constraints.

Practices like crop diversification (Auffhammer and Carleton 2018) or conservation-oriented agriculture involving minimum tillage, mulching with crop residue, and crop rotation (Michler et al. 2019) can mitigate the negative impacts of rainfall shocks. However, their adoption is impeded by lower levels of productivity in normal years making these practices costly. Hultgren et al. (2022) further validate these results and show that practices that adapt to rising temperatures also depress yields during periods of moderate temperatures. They also find that farmers are less capable of adapting to variations in seasonal precipitation, especially in drier and hotter regions. One explanation for the restricted effectiveness of adaptation practices is that weather uncertainty skews farmers' ability to evaluate and adopt the right practices. Burke and Emerick (2016) show that farmers in regions with lower variance in temperature, who could be more likely to diagnose climate change, also don't make significant adaptive investments to subsequent temperature increases.

Short-term adaptation approaches may sometimes bear other adverse consequences, for example, Fishman (2018) and Taraz (2017) show that while irrigation can somewhat offset the effects of variable precipitation, depleting groundwater levels leave agriculture more vulnerable to shocks in the longer run (Hornbeck and Keskin 2014). The returns to adaptive technologies such as irrigation can also be a function of frictions in other markets such as labour markets, leading to the substitution of inputs across space that discount the benefits of the technology as an adaptation strategy, making its adoption inefficient (Jones et al. 2022). Additionally, transitioning to non-agricultural sectors as groundwater wells run dry may be an incomplete and costly form of adaptation (Blakeslee et al. 2020).

Therefore, changing agricultural practices alone is not sufficient, but equipped with the right bundle of innovations, information, incentives, and insurance, new technologies and practices can be a powerful tool to mitigate climate risks. Encouraging locally-relevant agricultural innovations and building a policy space that facilitates their adoption are critical components of building local resilience (Suri and Udry 2022, Lybbert and Sumner 2012).

Recent work has also tested how firms can adapt to weather and climate shocks. Adhvaryu et al. (2020) find that adopting LED lights improves worker productivity in garment factories by lowering the ambient temperature, indicating that climate mitigation technologies (e.g. energy efficient lighting) can also aid adaptation in this case. Furthermore, workers themselves may adapt to growing heat by taking more breaks, which impacts aggregate productivity (Masuda et al. 2021). Air conditioning is another way for households to adapt to rising temperatures and reduce thermal discomfort, although its high costs imply concentrated adoption among richer households (Randazzo et al. 2021, Pavanello et al. 2021) and long-term consequences on burdening the electricity grid (Davis and Gertler 2015). While technological improvements can aid adaptation, innovation in this space remains limited, with the share of climate adaptation inventions in 2015 roughly the same as those in 1995 (Glachant 2020).

IIIC Governance and socio-economic policy

Greenstone and Jack (2015) categorise four components that determine the effectiveness of climate response, especially in developing countries: low-income levels, high costs of adaptation, political economy considerations, and market failures. Government policy is potentially a formidable tool that can shape and manipulate these components. To this end, Kahn (2005) finds that economic development and higher-quality institutions (as measured by a democracy measure, inequality, ethnic fragmentation, and the World Bank's good governance index) reduce deaths from natural disasters using cross-country panel data from 73 countries.

Large-scale infrastructure investments are a major portion of government public good provision in low- and middle-income countries, with over 80% of all infrastructure investments being state-financed and close to half of these being transport expenditures (Foster et al. 2022). Investments in transport and connectivity can mitigate the impacts of extreme weather through trade and market access channels. Burgess and Donaldson (2010) find that the colonial-era expansion of railroads in India curtailed the likelihood of famines caused by low rainfall by slashing transport costs for domestic trade. Seasonal floods in Nicaragua reduce labour market income by 18%, but building bridges to connect areas cut off by the floods eliminates this effect by improving labour market activity, farm investments, and household savings (Brooks and Donovan 2020). Apart from these market channels that facilitate recovery, infrastructure investments can also improve first responses to climate shocks. Del Valle et al. (2020) find that Mexico's indexed disaster fund allowed less-resilient municipalities to recover faster after a natural disaster, and Del Valle (*forthcoming*) finds that this fund also accelerated the reconstruction of infrastructure and mitigated mortality effects, especially in areas with accessible medical facilities. While the indexed disaster funds provide a novel way to build contingent liquidity for governments to deal with disasters, effective infrastructure investments are costly and difficult to implement, especially in rural areas.

Safety nets provided by social protection policies may mitigate the costs of climate shocks for vulnerable, poorer populations who otherwise lack the wherewithal to cope. Garg et al. (2020) show that workfare programmes, such as the employment guarantee programme in India, can attenuate the negative effect of rising temperatures on children's learning by supplementing household income. Liquidity transfers are, however, not a universal solution to facilitating climate resilience. Banerjee and Maharaj (2020) find that providing last-mile healthcare through community health workers in India was more effective in suppressing the negative impacts of rising temperatures on infant mortality than income gains from the same employment guarantee programme in India. Garg et al. (2020) also show that even though cash transfers attenuate homicide crimes that are driven by rising temperatures in the short run, the homicide rate reverses back to its original levels within 5 years of receiving access to a Progresa grant. More work needs to be done to understand the impacts of transfer programmes over time, when cash transfers are effective, and how social policy can be bolstered to equip vulnerable communities to face climate shocks.

A fundamental consideration in discussion of the government's role in building climate resilience is whether their own incentives are (1) aligned with promoting climate adaptation, and (2) flexible to respond to changing climate conditions. Government responses to weather shocks can also be driven by political economy concerns that operate during times of vulnerability from climate shocks (Mahadevan and Shenoy 2023, Tarquinio 2023, Bobonis et al. 2022, Fitch-Fleischmann and Kresh 2021, Cole et al. 2012). Coordination problems between sub-national jurisdictions persist, leading to continued negative externalities that depreciate essential resources like clean air, water, and forests (Dipoppa and Gulzar 2023, Bhogale and Khedgikar 2023, Burgess et al. 2012).

Therefore, recent literature highlights the progress in climate adaptation methodologies and sheds light on financial, physical, and policy instruments that are effective. However, a number of these come attached with short-term costs and uncertainty about long-term benefits. Climate adaptation, along with our understanding of what works, still remains substantially incomplete. In the next section, we review recent work on quantitative spatial general equilibrium models and climate change adaptation.

IV Spatial linkages and climate adaptation

Spatial linkages will be central in mediating the impacts of climate change, both via the role they may play in the transmission of climate shocks, and by facilitating adaptation. A growing literature has examined such effects, leveraging the increasing availability of global, spatially-explicit micro-data (see, for example, Auffhammer et al. 2013, Donaldson and Storeygard 2016), as well as recent advances in quantitative models of the spatial distribution of economic activity (reviewed in, for instance, Redding and Rossi-Hansberg 2017) to estimate aggregate and distributional implications for climate damages and adaptation policy.

IVA Spatial linkages and the transmission of climate shocks

The effects of climate shocks may be transmitted across regions, via general equilibrium adjustments, along a range of margins which have been investigated in recent empirical studies. Accounting for these responses has been found to have quantitatively meaningful implications for estimates of climate change damages and our understanding of adaptation requirements and mechanisms.

Trade channels have been found to be important in propagating and amplifying natural disaster shocks both within and across countries using firm-level micro-data. Barrot and Sauvagnat (2016) find that natural disaster shocks in the USA over the last 30 years that affect supplier firms in production networks also impose large downstream output losses on their customers, which result in substantial losses in the latter's market value and spill over to other suppliers. These effects are especially pronounced for suppliers producing specific inputs where few substitutable inputs are likely to be available. Consistent with this, two papers studying the 2011 Great East Japan Earthquake document evidence for substantial propagation effects both within Japan (Carvalho et al. 2021) and across countries (Boehm et al. 2019). Carvalho et al. (2021) find evidence for the propagation of the earthquake's effects both upstream and downstream along supply chains, with impacts felt on indirect and direct suppliers and customers of disaster-affected firms. Boehm et al. (2019) consider cross-country transmission of disruption induced by the earthquake via inelastic production linkages, primarily of multinational firms.

Migration is another channel via which spatial linkages may be important in transmitting the effects of climatic disasters across regions. Empirical studies spanning a range of contexts find evidence for out-migration responses following temperature extremes and natural disasters, the severity and frequency of which are projected to rise as the global climate changes (IPCC 2021). Missirian and Schlenker (2017) consider how weather variations in 103 source countries impacted asylum applications to the European Union from 2000 to 2014, finding that temperatures deviating from the moderate optimum increased asylum applications. Cai et al. (2016) find a positive relationship between temperature and international out-migration only in the most agriculture-dependent countries, and that this relationship follows a non-linear pattern consistent with non-linearities in the relationship between temperatures and agricultural yields. Similarly, Jessoe et al. (2016) find evidence for increased migration from Mexico's rural areas to the US (especially from regions close to the border) and to other domestic areas in years with high occurrences of hot days, causing labour supply shortages in the origin locations. A number of studies suggest that effects may be heterogeneous across disaster types, with evidence that migration responses to flooding may be more muted than those to heat stress in Pakistan (Mueller et al. 2014) or tornados in historical data from the USA (Boustan et al. 2012).

IVB Spatial linkages and adaptation to climate change

While spatial linkages play a role in transmitting climate shocks, they may also facilitate adaptation to their consequences. Climate change is projected to result in highly heterogeneous impacts across regions, sectors, and crops. In light of this, recent literature has considered the possibility that changes in the spatial distribution of economic activity may attenuate losses, and that trade and other linkages may mitigate the costs of reallocating consumption and production in response to climatic changes. These studies lean on quantitative spatial models, estimated using fine-grained data and empirical estimates of climate-induced changes, to project the implications of such general equilibrium adaptive adjustments for projected climate damages.

Costinot et al. (2016) estimate the macro-level consequences of micro-level climate change-induced shocks to crop yields, incorporating general equilibrium adjustments of trade and production. They use a spatial general equilibrium model together with micro-data on the productivity of each of the ten crops, before and after accounting for the future effects of climate change, for 1.7 million fields across the earth. The results suggest that climate change would result in a 0.26% reduction in global GDP through its effects on crop yields when incorporating adjustments in both trade and crop production choices across fields. While estimated declines are three times larger when crop production adjustments are shut down – highlighting the importance of this adaptive margin, in response to changing comparative advantage, in mitigating climate change impacts – only modestly larger declines are estimated when trade adjustments are shut down.

Gouel and Laborde (2021) also consider the livestock sector and find that trade adjustments may play a more substantial role in reducing projected losses via reallocation between import sources, rather than adjustments to the exported share of crops. Nath (2022) considers adjustments between agricultural and non-agricultural sectors and finds that sectoral reallocation may result in increases in estimated climate change losses due to the dominant effect of the so-called 'food problem' – whereby poorer countries specialise in low-productivity agriculture to meet subsistence needs – as climate change exacerbates this by pulling more labour into agriculture as productivity declines. Across these studies, the evidence suggests that there will be significant heterogeneity across regions: for example, Nath (2022) estimates that global losses are on average 17% higher when accounting for sectoral reallocation, but this rises to 49% in the poorest quartile of countries.

Firm-level adaptation to climate risk has also been examined through the lens of quantitative equilibrium models incorporating spatial linkages in recent literature. Balboni et al. (2023) combine data on the flood exposure of firms and transportation links in Pakistan, with a model of endogenous production network formation, and find that the impacts of climate change will be mediated as firms learn from the experience of increasingly frequent climate disasters. Jia et al. (2022) characterise how flood risk influences firms' location choices and workers' employment, and use this to estimate the aggregate impact of increased flood risk on the economy as the climate changes. Castro-Vincenzi (2023) uses the example of the global car industry to consider how firms redesign the organisation of plant networks and use their multi-plant structure to hedge when one of their plants faces an extreme weather event.

IVC Dynamic considerations

Given that many of the impacts of climate change are projected to be realised over several decades, or even centuries, dynamic considerations are central in estimating long-run changes and adaptation. Recent examinations of climate change adaptation have incorporated insights from frontier innovations using quantitative models of the spatial distribution of economic activity to combine spatial linkages with intertemporal decisions across locations.

One branch of this literature has used models accounting for individuals' expectations and the cost of trade and migration (see, for example, Artuc et al. 2010, Caliendo et al. 2019). Balboni (2021) uses such a setup together with district-level data from Vietnam to demonstrate that accounting for future sea level rise renders contemporary investments in road infrastructure significantly less valuable than when returns are estimated without considering the impacts of future inundation. Rudik et al. (2022) use such a framework to quantify the economic effects of climate change accounting for market-based adaptation through trade and labour migration, with a focus on the United States. Their estimates suggest that adaptation via these two channels is complementary, together increasing welfare by 50% more than the effects from each channel individually.

A second approach applied in a number of recent studies of adaptation to climate change instead models dynamics as arising from investments in local technology (Desmet et al. 2018). Firms can invest in improving technology, and regions are linked via trade, migration, and the diffusion of technology over time. This setup has been applied to the structural estimation of the effects of dynamic adaptation to sea level rise and global warming. Desmet et al. (2021) estimate the global consequences of sea level rise for 64,800 cells across the world accounting for dynamics of migration, trade, and innovation. Their results suggest a hugely important role for adaptation: the welfare costs of sea level rise are projected to be reduced fivefold in a model incorporating all adaptation channels compared to a naïve scenario with no adaptation. The significantly larger losses from sea level rise in the scenario ignoring dynamic spatial adjustments of the economy result from individuals being unable to migrate out of flooded locations, and foregone innovation in newly emerging clusters of economic activity. Cruz and Rossi-Hansberg (2023) extend the framework to incorporate energy as a factor of production and climate change impacts manifested via impacts of temperature on local productivities, amenities, and natality rates. The results suggest highly heterogeneous losses from global warming – with losses reaching 20% in areas of Africa and Latin America while some northern latitudes gain – but that migration and innovation can serve as important adaptation channels. Conte et al. (2021) add consideration of the impacts of changes in local specialisation, finding that trade costs make adaptation via changes in sectoral specialisation more costly, which reduces geographic concentration in agriculture and drives larger flows of climate migrants.

Recent work has drawn on theoretical advances combining forward-looking dynamic migration models with local capitalists who make dynamic consumption-investment decisions (Kleinman et al. 2023). Bilal and Rossi-Hansberg (2021) build on such a framework to demonstrate that climate impacts on capital depreciation and mobility magnify the aggregate welfare costs of climate change in the US, and that adaptation via migration and investment are central in mitigating climate damages.

IVD Implications for spatial policy and investment decisions

The structural modeling frameworks described above open up the possibility to simulate policy counterfactuals in order to assess how alternative adaptive policies and investments may influence the projected dynamic evolution of both the economy and aggregate welfare in the face of a changing climate. Desmet et al. (2021), for instance, highlight that estimated damages from sea level rise depend crucially on the magnitude of migration restrictions, estimating that prohibitive migration restrictions would lead to projected real GDP losses of 4.5% from sea level rise in 2200, relative to the baseline case of 0.11% in the benchmark model incorporating migration adjustments. Similarly, Conte (2022) uses a similar setup to estimate that reducing migration barriers from the standards in sub-Saharan Africa to those in the European Union eliminates the aggregate economic losses of climate change in sub-Saharan Africa, but at the expense of greater climate migration and regional inequality.

Government investment decisions can also be evaluated through the lens of these frameworks. Balboni (2021) finds that accounting for the projected impacts of future sea level rise leads to meaningful differences in assessments of where infrastructure should be allocated today. Hsiao (2023) considers how government intervention may complicate long-run adaptation to climate change by inducing coastal moral hazard, using the example of a proposed sea wall in Jakarta.

V Conclusion

In this section, we discuss possible directions for research that can contribute to our understanding of adaptation to climate change. The first is a deeper understanding of long-term impacts of climate change, as well as the mechanisms facilitating adaptation. Moreover, certain short-term adaptations, like irrigation, may have negative longer term consequences from depleting groundwater. Shedding light on what actions and policies empower agents to build sustained resilience is important, especially since evidence discussed in this review suggests that no isolated strategy leads to complete preparedness or recovery from a shock. Composite interventions like graduation programmes that include bundles of information, assets, and resources could play a vital role in overcoming climate vulnerability, as they have been effective in pushing people out of poverty traps. Testing similar programmes catered towards climate resilience could potentially improve our understanding of what works in the long-run.

In individual adaptation strategies, covering downside-risk through insurance or technology has emerged as a promising mitigation approach in the agricultural sector. They crowd-in investments and enhance productivity with and without weather shocks. The growing research on adoption has made progress in understanding the take-up of technologies, their underlying heterogeneity, and modes of dissemination, but in many settings, take-up of weather insurance remains low. The optimal design and outreach approach for climate insurance in different contexts remain elusive. Work in psychology and environmental management has discussed behavioural adaptation to climate change (see van Valkengoed and Steg 2019 for a meta analysis, and van Valkengoed et al. 2022 and Walawalkar et al. 2023 for reviews), which may be relevant for policies seeking to facilitate adaptation.

Furthermore, a deeper understanding of firms's adaptation to climate change could include areas such as the use of weather insurance, management practices and organisational structures, location of work (ranging from agglomeration of industries to work from home versus in-person work), and research and innovation in building firm's capacity in weathering climate shocks. Additionally, about 60% of the global workforce is employed in the informal sector, which contributes about 35% of the GDP in low and middle income countries (ILO 2018). Informality adds to the vulnerability to climate shocks in developing countries and more work is needed to understand how these populations can be covered despite climate change.

Current and future evidence on adaptation will translate into climate resilience largely through government policy. Policy is especially a powerful tool, since the same linkages that multiply the negative effects of climate shocks through migration and supply chains, can also multiply the efficiency of government policy in facilitating adaptation and mitigation. In democracies, we assume that the government's incentives are aligned with the long-term well-being of citizens and will accommodate climate adaptation. However, research suggests that political economy concerns may skew government interests away from long-term adaptation. There is currently a growing literature highlighting these political constraints, but more research on what conditions can align political motives with climate resilience would be highly policy relevant.

We conclude by emphasising four aspects of the literature on climate change adaptation in developing countries. First, climate change and weather shocks impact households, firms, and countries negatively across a range of first-order outcomes such as income and mortality. Second, these effects are usually quite large and can transmit across space via supply relationships or migration, and persist across time, including in some instances for decades. Third, while households, farmers, and firms undertake a variety of adaptation measures, these are seldom able to mitigate the impacts of climate completely, indicating that policies to facilitate adaptation will likely have large welfare gains. Fourth, while socio-economic policies can provide safety nets and minimise frictions that catalyse adaptation, political economy concerns may also shift the focus away from climate resilience. As developing countries begin to ramp up efforts to facilitate adaptation and receive international climate financing for adaptation, understanding how these can be best allocated to high-impact regions and policies should form a crucial set of questions for future work.

References

Acevedo, S, M Mrkaic, N Novta, M Poplawski-Ribeiro, E Pugacheva, and P Topalova (2017), "The Effects of Weather Shocks on Economic Activity: How Can Low-Income Countries Cope," World Economic Outlook.

Acevedo, S, M Mrkaic, N Novta, E Pugacheva, and P Topalova (2018), "The Effects of Weather Shocks on Economic Activity: What are the Channels of Impact?", IMF Working Paper.

Adhvaryu, A, N Kala, and A Nyshadham (2020), "The Light and the Heat: Productivity Co-benefits of Energy-saving Technology," *Review of Economics and Statistics*, 102(4): 779-792.

Ahmed, S, C Mcintosh, and A Sarris (2020), "The Impact of Commercial Rainfall Index Insurance: Experimental Evidence from Ethiopia," *American Journal of Agricultural Economics*, 102(4): 1154-1174.

Annan, F, E Klobodu, and J Schrader (2023), "Competition Constraints Adaptation to Climate Shocks," Working Paper.

Artuç, E, S Chaudhuri, and J McLaren (2010), "Trade Shocks and Labor Adjustment: A Structural Empirical Approach," *American Economic Review*, 100(3): 1008-1045.

Auffhammer, M, S M Hsiang, W Schlenker, and A Sobel (2013), "Using Weather Data and Climate Model Output in Economic Analyses of Climate Change," *Review of Environmental Economics and Policy*.

Auffhammer, M and T A Carleton (2018), "Regional Crop Diversity and Weather Shocks in India," *Asian Development Review*, 35(2): 113–130.

Baez, J E, and I V Santos (2007), "Children's Vulnerability to Weather Shocks: A Natural Disaster as a Natural Experiment," Social Science Research Network, New York: 1-28.

Balboni, C (2021), "In Harm's Way? Infrastructure Investments and the Persistence of Coastal Cities," Working Paper.

Balboni, C, J Boehm, and M Waseem (2023), "Firm Adaptation in Production Networks: Evidence from Extreme Weather Events in Pakistan", Working Paper.

Balboni, C, R Burgess, A Heil, J Old, and B A Olken (2021b), "Cycles of Fire? Politics and Forest Burning in Indonesia," *AEA Papers and Proceedings*, 111: 415-419.

Banerjee, R, and R Maharaj (2020), "Heat, Infant Mortality, and Adaptation: Evidence from India," *Journal of Development Economics*, 143: 102378.

Bardhan, P (1983), "Labor-tying in a Poor Agrarian Economy: A Theoretical and Empirical Analysis," *Quarterly Journal of Economics*, 98(3): 501–514.

Barrot, J-N and J Sauvagnat (2016), "Input Specificity and the Propagation of Idiosyncratic Shocks in Production Networks," *Quarterly Journal of Economics*, 131(3): 1543–1592.

Beg, S (2022), "Digitization and Development: Property Rights Security, and Land and Labor Markets," *Journal of the European Economic Association*, 20(1): 395-429.

Bento, A, N S Miller, M Mookerjee, and E R Severnini (2020), "A Unifying Approach to Measuring Climate Change Impacts and Adaptation," National Bureau of Economic Research, w27247.

Besley, T (1995), "Savings, Credit and Insurance," *Handbook of Development Economics*, 3: 2123-2207.

Bhogale, S, and S Khedgikar (2023), "Run On The Reservoir: Evidence for Administrative Competition for Groundwater in India," Working Paper.

Bilal, A, and E Rossi-Hansberg (2021), "Location as an Asset," *Econometrica*, 85(5): 2459–2495.

Blakeslee, D, and R Fishman (2018), "Weather Shocks, Agriculture, and Crime Evidence from India," *Journal of Human Resources*, 53(3): 750-782.

Blakeslee, D, R Fishman, and V Srinivasan (2020), "Way Down in the Hole: Adaptation to Long-Term Water Loss in Rural India," *American Economic Review*, 110(1): 200-224.

Bobonis, G J, P J Gertler, M Gonzalez-Navarro, and S Nichter (2022), "Vulnerability and Clientelism," *American Economic Review*, 112(11): 3627-3659.

Boehm, C E, A Flaaen, and N Pandalai-Nayar (2019), "Input Linkages and the Transmission of Shocks: Firm-Level Evidence from the 2011 Tōhoku Earthquake," *Review of Economics and Statistics*, 101(1): 60-75.

Boustan, L P, M E Kahn, and P W Rhode (2012), "Moving to Higher Ground: Migration Response to Natural Disasters in the Early Twentieth Century," *American Economic Review*, 102(3): 238–244.

Brooks, W, and K Donovan (2020), "Eliminating Uncertainty in Market Access: The Impact of New Bridges in Rural Nicaragua," *Econometrica*, 88(5): 1965–1997.

Burgess, R, and D Donaldson (2010), "Can Openness Mitigate the Effects of Weather Shocks? Evidence from India's Famine Era," American Economic Review, 100(2): 449-53.

Burgess, R, M Hansen, B A Olken, P Potapov, and S Sieber (2012), "The Political Economy of Deforestation in the Tropics," *Quarterly Journal of Economics*, 127(4): 1707-1754.

Burgess, R, O Deschenes, D Donaldson, and M Greenstone, "Weather, Climate Change and Death in India," University of Chicago, 2017.

Burke, M, and K Emerick (2016), "Adaptation to Climate Change: Evidence from US Agriculture." *American Economic Journal: Economic Policy* 8(3): 106-140.

Burke, M, S M Hsiang, and E Miguel (2015), "Climate and Conflict," *Annu. Rev. Econ*., 7(1): 577-617.

Cai, R, S Feng, M Oppenheimer, and M Pytlikova (2016), "Climate Variability and International Migration: The Importance of the Agricultural Linkage," *Journal of Environmental Economics and Management*, 79: 135–151.

Caliendo, L, M Dvorkin, and F Parro (2019), "Trade and Labor Market Dynamics: General Equilibrium Analysis of the China Trade Shock," *Econometrica*, 87(3): 741–835.

Caruso, G D (2017), "The Legacy of Natural Disasters: The Intergenerational Impact of 100 Years of Disasters in Latin America", Working Paper.

Carvalho, V M, M Nirei, Y U Saito, and A Tahbaz-Salehi (2021), "Supply Chain Disruptions: Evidence from the Great East Japan Earthquake," *Quarterly Journal of Economics*, 136(2): 1255–1321.

Casaburi, L, and J Willis (2018), "Time versus State in Insurance: Experimental Evidence from Contract Farming in Kenya," *American Economic Review*, 108(12): 3778-3813.

Castro-Vincenzi, J (2023), "Climate Hazards and Resilience in the Global Car Industry," Working Paper.

Cole, S, A Healy, and E Werker (2012), "Do Voters Demand Responsive Governments? Evidence from Indian Disaster Relief," *Journal of Development Economics*, 97(2): 167-181.

Cole, S, X Giné, J Tobacman, P Topalova, R Townsend, and J Vickery (2013), "Barriers to Household Risk Management: Evidence from India," *American Economic Journal: Applied Economics*, 5(1): 104–135.

Colmer, J (2021), "Temperature, Labor Reallocation, and Industrial Production: Evidence from India," *American Economic Journal: Applied Economics*, 13(4): 101-124.

Conley, T, and C Udry (2001), "Social Learning through Networks: The Adoption of New Agricultural Technologies in Ghana," *American Journal of Agricultural Economics*, 83(3): 668–673.

Conte, B (2022), "Climate Change and Migration: The Case of Africa," Working Paper.

Conte, B, K Desmet, D K Nagy, and E Rossi-Hansberg (2021), "Local Sectoral Specialization in a Warming World," *Journal of Economic Geography*, 21(4): 493-530.

Costinot, A, D Donaldson, and C Smith (2016), "Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from 1.7 Million Fields around the World," *Journal of Political Economy*, 124(1): 205–248.

Cruz, J-L, & E Rossi-Hansberg (2023), "The Economic Geography of Global Warming," *Review of Economic Studies*.

Dar, M H, A de Janvry, K Emerick, D Raitzer, and E Sadoulet (2013), "Flood-Tolerant Rice Reduces Yield Variability and Raises Expected Yield, Differentially Benefitting Socially Disadvantaged Groups," *Scientific Reports*, 3(1): 3315.

Davis, L W, & P J Gertler (2015), "Contribution of Air Conditioning Adoption to Future Energy Use Under Global Warming," *Proceedings of the National Academy of Sciences*, 112(19): 5962-5967.

De Mel, S, D McKenzie, and C Woodruff (2012), "Enterprise Recovery Following Natural Disasters," *Economic Journal*, 122(559): 64-91.

Del Valle, Alejandro, Alain de Janvry, and Elisabeth Sadoulet. 2020. "Rules for Recovery: Impact of Indexed Disaster Funds on Shock Coping in Mexico," *American Economic Journal: Applied Economics*, 12 (4): 164-95.

Del Valle, A (forthcoming), "Saving Lives with Indexed Disaster Funds: Evidence from Mexico," *American Economic Journal: Economic Policy*.

Dell, M, B F Jones, and B A Olken (2012), "Temperature Shocks and Economic Growth: Evidence from the Last Half-century," *American Economic Journal: Macroeconomics*, 4(3): 66-95.

Deschênes, O, and M Greenstone (2007), "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather," *American Economic Review*, 97(1): 354-385.

Deschênes, O, and M Greenstone (2012), "The Economic Impacts of Climate Change: Evidence from

Agricultural Output and Random Fluctuations in Weather: Reply," *American Economic Review*, 102(7): 3761-3773.

Desmet, K, D K Nagy, and E Rossi-Hansberg (2018), "The Geography of Development," *Journal of Political Economy*, 126(3): 903–983.

Desmet, K, R E Kopp, S A Kulp, D K Nagy, M Oppenheimer, E Rossi-Hansberg, and B H Strauss (2021), "Evaluating the Economic Cost of Coastal Flooding," *American Economic Journal: Macroeconomics*, 13(2): 444–486.

Dipoppa, G, and S Gulzar (2023), "Administrative Incentives Impact Crop-Residue Burning and Health in South Asia," Working Paper.

Donaldson, D, and A Storeygard (2016), "The View From Above: Applications of Satellite Data in Economics," *Journal of Economic Perspectives*, 30(4): 171-198.

Elabed, G, & M Carter (2014), "Ex-ante Impacts of Agricultural Insurance: Evidence From a Field Experiment in Mali," Working Paper.

Elliott, R J R, E Strobl, and P Sun (2015), "The Local Impact of Typhoons on Economic Activity in China: A View From Outer Space," *Journal of Urban Economics*, 88: 50-66.

Emerick, K, A de Janvry, E Sadoulet, and M H Dar (2016), "Technological Innovations, Downside Risk, and the Modernization of Agriculture," *American Economic Review*, 106(6): 1537-1561.

Emerick, K, and M H Dar (2021), "Farmer Field Days and Demonstrator Selection for Increasing Technology Adoption," *Review of Economics and Statistics*, 103(4): 680–693.

Fafchamps, M (1993), "Sequential Labor Decisions Under Uncertainty: An Estimable Household Model of West-African Farmers," *Econometrica*, 61(5): 1173–1197.

Fafchamps, M, C Udry, and K Czukas (1998), "Drought and Saving in West Africa: Are Livestock a Buffer Stock?" *Journal of Development Economics*, 55: 273-305.

Fisher, A C, W M Hanemann, M J Roberts, and W Schlenker (2012), "The Economic Impacts of Climate Change: Evidence From Agricultural Output and Random Fluctuations in Weather: Comment," *American Economic Review*, 102(7): 3749-3760.

Fishman, R (2018), "Groundwater Depletion Limits the Scope for Adaptation to Increased Rainfall Variability in India," *Climatic Change*, 147: 195–209.

Fishman, R, P Carrillo, and J Russ (2019) "Long-term impacts of exposure to high temperatures on human capital and economic productivity," *Journal of Environmental Economics and Management*, 93: 221-238.

Fitch-Fleischmann, B and E P Kresch (2021), "Story of the hurricane: Government, NGOs, and the difference in disaster relief targeting," *Journal of Development Economics*, 152 (102702).

Foster, A D, and M R Rosenzweig (1995), "Learning by Doing and Learning From Others: Human Capital and Technical Change in Agriculture," *Journal of Political Economy*, 103(6): 1176–1209.

Foster, V, A Rana, and N Gorgulu (2022), "Understanding Public Spending Trends for Infrastructure in Developing Countries," Working Paper.

Garg, T, M Jagnani, and V Taraz (2020), "Temperature and Human Capital in India," *Journal of the Association of Environmental and Resource Economists*, 7(6): 1113-1150.

Garg, T, G C McCord, and A Montfort (2020), "Can Social Protection Reduce Environmental Damages?" Working Paper.

Geruso, M, and D Spears (2018), "Heat, Humidity, and Infant Mortality in the Developing World," National Bureau of Economic Research.

Glachant, M (2020), "Innovation in Climate Change Adaptation: Does It Reach Those Who Need It Most?" World Bank Blogs.

Glennerster, R, and T Suri (2018), "Agricultural Technology and Nutrition: The Impacts of NERICA Rice in Sierra Leone," Working Paper.

Gouel, C, and D Laborde (2021), "The Crucial Role of Domestic and International Market-mediated Adaptation to Climate Change," *Journal of Environmental Economics and Management*, 106: 102408.

Graff Zivin, J, and M Neidell (2014), "Temperature and the Allocation of Time: Implications for Climate Change," *Journal of Labor Economics*, 32(1): 1–26.

Greenstone, M, and B K Jack (2015), "Envirodevonomics: A Research Agenda for an Emerging Field," *Journal of Economic Literature*, 53(1): 5-42.

Guha-Sapir, D, R Below, and P Hoyois (2023), "EM-DAT: The CRED/OFDA International Disaster Database", Université Catholique de Louvain – Brussels – Belgium.

Guiteras, R (2009), "The Impact of Climate Change on Indian Agriculture," Manuscript, Department of Economics, University of Maryland, College Park, Maryland.

Hanna, R, and P Oliva (2016), "Implications of Climate Change for Children in Developing Countries," *The Future of Children*: 115-132.

He, H, S Wang, and B Zhang (2020), "Watering Down Environmental Regulation in China," *Quarterly Journal of Economics*, 135(4): 2135-2185.

Henderson, J V, A Storeygard, and U Deichmann (2017), "Has Climate Change Driven Urbanization in Africa?" *Journal of Development Economics*, 124: 60–82.

Hornbeck, R, and P Keskin (2014), "The Historically Evolving Impact of the Ogallala Aquifer: Agricultural Adaptation to Groundwater and Drought," *American Economic Journal: Applied Economics*, 6(1): 190-219.

Hsiang, S M, and A S Jina (2014), "The Causal Effect of Environmental Catastrophe on Long-run Economic Growth: Evidence from 6,700 Cyclones," National Bureau of Economic Research.

Hsiang, S M, M Burke, and E Miguel (2013), "Quantifying the Influence of Climate on Human Conflict," Science, 341(6151): 1235367.

Hsiao, A (2023), "Sea Level Rise and Urban Adaptation," Working Paper.

Hultgren, A, T Carleton, M Delgado, D R Gergel, M Greenstone, T Houser, S Hsiang, A Jina, R E Kopp, S B Malevich, K McCusker, T Mayer, I Nath, J Rising, A Rode, and J Yuan (2022), "Estimating Global Impacts to Agriculture from Climate Change Accounting for Adaptation," Available at SSRN.

ILO (2018), "Women and men in the informal economy: A statistical picture." Third edition.

IPCC (2014), "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change". IPCC AR5 Synthesis Report.

Jessoe, K, D T Manning, J E Taylor (2016), "Climate Change and Labour Allocation in Rural Mexico: Evidence from Annual Fluctuations in Weather", *Economic Journal*, 126(608): 230-261.

Jia, R, X Ma, and V W Xie (2022), "Expecting Floods: Firm Entry, Employment, and Aggregate Implications," Working Paper.

Jones, M, F Kondylis, J Loeser, and J Magruder (2022), "Factor Market Failures and the Adoption of Irrigation in Rwanda," *American Economic Review*, 112(7): 2316-52.

Kahn, M E (2005), "The Death Toll from Natural Disasters: The Role of Income, Geography, and Institutions," *Review of Economics and Statistics*, 87(2): 271–284.

Kala, N (2017), "Learning, Adaptation, and Climate Uncertainty: Evidence from Indian Agriculture," MIT Center for Energy and Environmental Policy Research, Working Paper 23.

Karlan, D, R Osei, I Osei-Akoto, and C Udry (2014), "Agricultural Decisions After Relaxing Credit and Risk Constraints," *Quarterly Journal of Economics*, 129(2): 597-652.

Kleinman, B, E Liu, and S J Redding (2023), "Dynamic Spatial General Equilibrium," *Econometrica*, 91(2): 385-424.

Kochar, A (1999), "Smoothing Consumption by Smoothing Income: Hours-of-Work Responses to Idiosyncratic Agricultural Shocks in Rural India," *Review of Economics and Statistics*, 81(1): 50–61.

Kurukulasuriya, P, N Kala, and R Mendelsohn (2011), "Adaptation and Climate Change Impacts: A Structural Ricardian Model of Irrigation and Farm Income in Africa," *Climate Change Economics*, 2(2): 149-174.

Lane, G (2023), "Adapting to Floods with Guaranteed Credit: Evidence from Bangladesh," Working Paper.

Legg, S (2022), "IPCC, 2021: Climate Change 2021-The Physical Science Basis," *Interaction*, 49(4): 44-45.

Lemoine, D (2018), "Estimating the Consequences of Climate Change From Variation in Weather," National Bureau of Economic Research, No. w25008.

Liu, M, Y Shamdasani, and V Taraz (2023), "Climate Change and Labor Reallocation: Evidence From Six Decades of the Indian Census," *American Economic Journal: Economic Policy*, 15(2): 395-423.

Lybbert, T, and D Sumner (2012), "Agricultural Technologies for Climate Change in Developing Countries: Policy Options for Innovation and Technology Diffusion," *Food Policy*, 37(1): 114-123.

Maccini, S, and D Yang (2009), "Under the Weather: Health, Schooling, and Economic Consequences of Early-life Rainfall," *American Economic Review*, 99(3): 1006-1026.

Macours, K, P Premand, and R Vakis (2022), "Transfers, Diversification, and Household Risk Strategies: Can Productive Safety Nets Help Households Manage Climatic Variability?" *Economic Journal*, 132(647):

2438–2470.

Mahadevan, M, and A Shenoy (2023), "The Political Consequences of Resource Scarcity: Targeted Spending in a Water-stressed Democracy," *Journal of Public Economics*, 220: 104842.

Masuda, Y J, T Garg, I Anggraeni, K Ebi, J Krenz, E T Game, N H Wolff, and J T Spector (2021), "Warming From Tropical Deforestation Reduces Worker Productivity in Rural Communities," *Nature Communications*, 12(1): 1601.

Matsuyama, K (1992), "Agricultural Productivity, Comparative Advantage, and Economic Growth," *Journal of Economic Theory*, 58(2): 317-334.

McGuirk, E F, and N Nunn (2021), "Transhumant Pastoralism, Climate Change, and Conflict in Africa," Working Paper.

McIntosh, C, F Povel, and E Sadoulet (2019), "Utility, Risk, and Demand for Incomplete Insurance: Lab Experiments with Guatemalan Co-Operatives," *Economic Journal*, 129(622): 2581–2607.

Mendelsohn, R, W D Nordhaus, and D Shaw (1994), "The Impact of Global Warming on Agriculture: A Ricardian Analysis," *American Economic Review*: 753-771.

Michler, J D, K Baylis, M Arends-Kuenning, and K Mazvimavi (2019), "Conservation Agriculture and Climate Resilience," *Journal of Environmental Economics and Management*, 93: 148–69.

Miguel, E (2005), "Poverty and Witch Killing," *Review of Economic Studies*, 72(4): 1153-1172.

Missirian, A, and W Schlenker (2017), "Asylum Applications Respond to Temperature Fluctuations," *Science*, 358(6370): 1610-1614.

Mobarak, A M and M R Rosenzweig (2013), "Informal Risk Sharing, Index Insurance, and Risk Taking in Developing Countries," *American Economic Review*, 103(3): 375–380.

Morduch, J (1995), "Income Smoothing and Consumption Smoothing," *Journal of Economic Perspectives*, 9(3): 103-114.

Moscona, J, and K Sastry (2022), "Inappropriate Technology: Evidence from Global Agriculture," Working Paper.

Mueller, V, C Gray, and K Kosec (2014), "Heat Stress Increases Long-term Human Migration in Rural Pakistan," *Nature Climate Change*, 4(3): 182–185.

Munshi, K (2004), "Social Learning in a Heterogeneous Population: Technology Diffusion in the Indian Green Revolution," *Journal of Development Economics*, 73(1): 185-213.

Nath, I (2022), "Climate Change, The Food Problem, and the Challenge of Adaptation through Sectoral Reallocation," US Census Bureau, Center for Economic Studies.

Pavanello, F, E De Cian, M Davide, M Mistry, T Cruz, P Bezerra, D Jagu, S Renner, R Schaeffer, and A FP Lucena (2021), "Air-conditioning and the Adaptation Cooling Deficit in Emerging Economies," *Nature Communications*, 12: 6460.

Pelli, M, J Tschopp, N Bezmaternykh, and K Eklou (2023), "In the Eye of the Storm: Firms and Capital Destruction in India," *Journal of Urban Economics*, 134: 103529.

Pople, A, R Hill, S Dercon, and B Brunckhorst (2023), "Anticipatory Cash Transfers in Climate Disaster Response," Working Paper.

Randazzo, T, F Pavanello, and E De Cian (2021), "Adaptation to Climate Change: Air-conditioning and the Role of Remittances," Working Paper.

Redding, S J, and E Rossi-Hansberg (2017), "Quantitative Spatial Economics," *Annual Review of Economics*, 9: 21-58.

Rosenzweig, C, J Elliott, D Deryng, A C Ruane, C Müller, A Arneth, K J Boote, C Folberth, M Glotter, N Khabarov, et al. (2014), "Assessing Agricultural Risks of Climate Change in the 21st century in a Global Gridded Crop Model Intercomparison," *Proceedings of the National Academy of Sciences*, 111(9): 3268-3273.

Rosenzweig, M, and C R Udry (2013), "Forecasting Profitability," National Bureau of Economic Research, No. w19334.

Rosenzweig, M, and H P Binswanger (1993), "Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments," *Economic Journal*, 103(416): 56–78.

Rosenzweig, M R, and K I Wolpin (1993), "Credit Market Constraints, Consumption Smoothing, and the Accumulation of Durable Production Assets in Low-Income Countries: Investments in Bullocks in India," *Journal of Political Economy*, 101(2): 223–244.

Rosenzweig, M, and O Stark (1989), "Consumption Smoothing, Migration, and Marriage: Evidence from Rural India," *Journal of Political Economy*, 97(4): 905-926.

Rudik, I, G Lyn, W Tan, and A Ortiz-Bobea (2022), "The Economic Effects of Climate Change in Dynamic Spatial Equilibrium," Working Paper.

Santangelo, G (2019), "Firms and Farms: The Local Effects of Farm Income on Firms' Demand," Working Paper.

Sekhri, S, and A Storeygard (2014), "Dowry deaths: Response to weather variability in India", *Journal of Development Economics* 111: 212-223.

Seo, S N, R Mendelsohn, and M Munasinghe (2005), "Climate Change and Agriculture in Sri Lanka: a Ricardian Valuation," *Environment and Development Economics*, 10(5): 581-596.

Severen, C, C Costello, and O Deschenes (2018), "A Forward-Looking Ricardian Approach: Do Land Markets Capitalize Climate Change Forecasts?", *Journal of Environmental Economics and Management*, 89: 235-254.

Shah, M, and B M Steinberg (2017), "Drought of Opportunities: Contemporaneous and Long-term Impacts of Rainfall Shocks on Human Capital," *Journal of Political Economy*, 125(2): 527-561.

Shrader, J (2017), "Expectations and Adaptation to Environmental Risks," Working Paper.

Suri, T (2011), "Selection and Comparative Advantage in Technology Adoption," *Econometrica*, 79(1): 159–209.

Suri, T, and C Udry (2022), "Agricultural Technology in Africa," *Journal of Economic Perspectives*, 36(1): 33-56.

Somanathan, E, R Somanathan, A Sudarshan, and M Tewari (2021), "The Impact of Temperature on Productivity and Labor Supply: Evidence from Indian Manufacturing," *Journal of Political Economy*, 129(6): 1797-1827.

Taraz, V (2017), "Adaptation to Climate Change: Historical Evidence From the Indian Monsoon," *Environment and Development Economics*, 22(5): 517–545.

Tarquinio, L (2023), "The Politics of Drought Relief: Evidence from Southern India," Working Paper.

van Valkengoed, A M and L Steg (2019), "Meta-Analyses of Factors Motivating Climate Change Adaptation Behaviour," *Nature Climate Change* 9(2): 158–163.

van Valkengoed, A M, W Abrahamse, and L Steg (2022), "To select effective interventions for pro-environmental behaviour change, we need to consider determinants of behaviour," *Nat Hum Behav* 6: 1482–1492.

Walawalkar, T, L Hermans, and J Evers (2023), "Evaluating behavioural changes for climate adaptation planning," *Journal of Environmental Planning and Management*, 66(7): 1453-1471.

World Bank (2020), "Monitoring Global Poverty."

Zheng, P, O Deschenes, K Meng, and J Zhang (2018), "Temperature effects on productivity and factor reallocation: Evidence from a half million chinese manufacturing plants", *Journal of Environmental Economics and Management*, 88:1-17.