Climate change, migration, and irrigation

March 19, 2019

Abstract

A rapidly growing literature demonstrates that climate change will affect both international and internal migration. Earlier work has found important evidence of a climate-migration poverty trap: higher temperatures reduce agricultural yields, which in turn reduce emigration rates in low-income countries, due to liquidity constraints (Cattaneo and Peri, 2016). On the other hand, other research demonstrates that irrigation can be effective in protecting agricultural yields from high temperatures. In this paper, we explore the juxtaposition of these two facts. We test whether access to irrigation modulates the climate-migration poverty trap. Specifically, we test whether having access to irrigation makes migration less sensitive to high temperature shocks. Using a global data set on poor and middle-income countries and a fixed effects framework, we regress decadal international migration data on decadal averages of temperature and rainfall, interacted with country-level data on irrigated areas and income levels. We also analyze urbanization rates, which we take as a proxy for rural-to-urban internal migration. Our study finds that access to irrigation significantly weakens the climate-migration poverty trap, demonstrating a potentially important protective role for irrigation in the context of climate-induced migration. Our results demonstrate that other scholars working on climate and migration should be sure to consider the role of irrigation in modulating those relationships. From a policy point of view, our results suggest that increasing access to irrigation may have spillover effects onto migration.

More broadly, our results speak to the need of simultaneously considering multiple adaptive responses when analyzing environmental challenges faced in developing countries.

JEL Classification: F22, O13, Q15, Q54, Q56

Keywords: international migration, rural-urban migration, climate change, agriculture, irrigation

1 Introduction

The development community has been addressing the issue of sustainable development for decades (see, for example, Lélé (1991)), a commitment that has culminated in the widely publicized Sustainable Development Goals (SDGs), set by the United Nations General Assembly in 2015. The acceleration of climate change necessitates that sustainable development directly address climate change: how climate change will impact households in developing countries, how households will adapt to climate change, and, importantly, how the process of climate change will affect and interact with the broader process of development. SDG 13 addresses climate change and calls on all countries to "strengthen resilience and adaptive capacity to climate-related hazards and natural disasters."

A key concern related to climate change is environmental migration (IPCC, 2014). Extensive ongoing research addresses this topic. For example, Missirian and Schlenker (2017) project that refugee applications into the European Union could almost double by the end of this century if current warming trends continue. A rapidly growing literature analyzes migration and climatic factors and explores the mechanisms underlying the climate–migration relationship (Barrios et al., 2006; Marchiori et al., 2012; Gray and Mueller, 2012a,b; Mueller et al., 2014; Bohra-Mishra et al., 2014; Beine and Parsons, 2015; Backhaus et al., 2015; Coniglio and Pesce, 2015; Feng et al., 2015; Cai et al., 2016; Cattaneo and Peri, 2016; Thiede et al., 2016; Dallmann and Millock, 2017; Jessoe et al., 2017; Missirian and Schlenker, 2017).

This literature demonstrates that agricultural incomes are an important force driving the climate–migration relationship (Cai et al., 2016; Missirian and Schlenker, 2017). The literature also demonstrates that the relationship between temperatures, migration, and income is hump-shaped: higher temperatures depress emigration from low-income countries, due to poverty traps, but increase it in middle-income countries, due to reduced returns to farming (Cattaneo and Peri, 2016). However, this literature has largely overlooked how migration, as a form of climate change adaptation, interacts with other adaptive responses to climate change. In particular, it is important to consider irrigation, which has been documented to cushion the negative effect of climate variability on plant growth (Siebert et al., 2017). To date, irrigation, a critical agricultural factor, has not yet been fully incorporated into international migration analysis.

In this paper, we test how international migration and urbanization respond to slow changes in weather, how this response varies by income level, and the extent to which access to irrigation modulates the response. Significantly, we replicate the poverty trap finding of Cattaneo and Peri (2016)—that higher temperatures reduce emigration rates in low-income countries—but find that access to irrigation significantly weakens this poverty trap, demonstrating an important protective role for irrigation in the context of climate-induced migration.

We develop a simple, two-period model that links access to irrigation, agricultural productivity, and the decision to migrate. Access to irrigation cushions agricultural productivity from adverse changes in weather factors (increased temperatures or reduced rainfall), while agricultural productivity itself influences the migration decision, in a hump-shaped model that follows Roy (1951) and Borjas (1987). The model predicts that adverse changes in the weather factors will reduce migration rates in low-income countries, due to a poverty trap mechanism, but that irrigation assets will dampen this effect.

Our empirical strategy involves two phases. First, we regress annual crop yields on weather, a measure of access to irrigation, and additional controls to demonstrate the protective effect of irrigation against weather sensitivity. To reduce endogeneity, we measure irrigation as the fraction of 1970's cropland that was irrigated. Second, we regress decadal emigration rates on a triple interaction of decadal changes in weather, a low-income country dummy, and the fraction of irrigated cropland in 1970. We include country fixed effects and decade fixed effects and rely on decadal fluctuations in weather for identification. We use decadal data on bilateral migrant stocks from Özden et al. (2011), urbanization rates[1]

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[1] We analyse the effect on urbanization rates as a proxy for rural-urban migration. Despite high natural urban population growth rates, rural-urban migration is the main factor of urbanization (Jedwab et al., 2017).

from the World Urbanization Prospects (UN, 2014), GDP data from the Penn World Tables (Feenstra et al., 2015), weather data from the University of Delaware (Willmott and Matsuura, 2018), data on irrigated areas from Siebert et al. (2015), and cereal yield data from the World Bank (2017). The final sample consists of 105 poor and middle-income countries, after excluding high fuel-exporters since they have little cropland and the share of irrigation is close to one in those countries.[2]

Our preliminary results are as follows. Our yield regressions demonstrate that higher temperatures reduce crop yields, but that irrigation assets diminish this effect. This result is robust to the inclusion of controls for GDP, allaying possible concerns that irrigation is merely a proxy for the general level of development of a country. Turning to migration, we replicate Cattaneo and Peri (2016) and demonstrate that higher temperatures decrease emigration rates in low-income countries. Next, we disaggregate further, looking at the triple interaction of weather, a low-income country dummy, and the share of irrigated cropland. In this specification, we find that the temperature-induced poverty trap in low-income countries is weakened when those countries have access to irrigation. When testing for the effect of irrigation on urbanization rates, we find an even stronger protective effect of irrigation.

Through this analysis we contribute to a multidisciplinary literature that explores climate change adaptation from a sustainable development lens. Relevant papers in the literature include Agrawal and Lemos (2015) who define and explore the concept of adaptive development, Castells-Quintana et al. (2018) who provide a helpful summary of the climate change adaptation literature, through a development economics lens, and Lemos et al. (2013) who explore how to build adaptive capacity in developing countries.

Within the climate change adaptation literature, we also contribute to the literature on climate-induced migration. The literature on environmental migration is reviewed in Millock (2015). The key papers that we relate to on international migration include Beine and Parsons (2015), who find no direct impact of temperature or precipitation anomalies on long-

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[2] The definition of high fuel-exporters are countries with fuel exports above 40% of GDP in 2000 according to the World Development Indicators.

term international migration rates, but find significant indirect effects of weather anomalies and natural disasters on the wage ratio and that natural disasters increase urbanization rates in developing countries; Cattaneo and Peri (2016) who find that higher temperatures increase urbanization rates and international migration from middle-income countries but decrease rural-urban and international migration from the poorest countries in the world; and Cai et al. (2016) who find that higher temperatures in the origin country increase annual bilateral migration rates but only in agriculture-dependent countries. We also complement district-level analysis from India that suggests that access to groundwater reduces internal migration (Fishman et al., 2017; Zaveri et al., 2018).

Our paper makes three important contributions to the literature. First, we are the first paper to integrate irrigation access into the analysis of international migration. We demonstrate that having access to irrigation can be complementary to migration and that poor countries with high levels of irrigation are not subject to as strong of a migration poverty trap as poor countries with low levels of irrigation are. Second, our paper shows that the cushioning effect of irrigation on temperature increases is larger for rural-urban migration than for international migration. Rural-urban migration is considered the most likely migration response following climate change (Barrios et al., 2006; Rigaud et al., 2018).[3] Third, our paper demonstrates and emphasizes the importance of considering multiple adaptation options in the context of climate change, an approach that is relevant for future scholarship.

The rest of the paper is organized as follows. Section 2 provides additional background on water scarcity, irrigation, and migration. In Section 3, we develop a model of the migration decision that incorporates wealth levels and access to irrigation. Section 4 describes the data sources used and presents summary statistics. In Section 5, we outline our empirical strategy. In Section 6, we present the results and run robustness checks. In Section 7, we discuss the limitations of the analysis and some of the broader implications for climate change adaptation. In Section 8, we conclude and propose suggestions for future research.

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[3] Henderson et al. (2017) show that the urbanization effect depends on whether the cities have manufacturing activity or not.

2 Background

Currently, two thirds of the global population live under conditions of severe water scarcity at least one month per year, and half a billion people face severe water scarcity all year round (Mekonnen and Hoekstra, 2016). Climate change and increasing water scarcity are likely to severely affect agricultural outcomes and food security, and hence have consequences on population mobility. Current adaptation methods in agriculture include intensification by the use of fertilizers or high-yield varieties of seed. Irrigation is another means to improve agricultural productivity, which has been important in arid and semi-arid regions of the world historically. In fact, irrigation contributes to 40% of the total food produced worldwide although irrigated agriculture only represents 20% of the total cultivated land (Vörosmarty and Green, 2000; FAO, 2014).

The protective effect of irrigation on crop yields is well-known from empirical work on climate change impacts across Africa (Kurukulasuriya et al., 2006) and India (Taraz, 2018). Irrigation acts as a form of self-insurance, since irrigating farmers typically have higher mean yields and lower variance of profits (Troy et al., 2015; Foudi and Erdlenbruch, 2011). The self-insurance aspect is important, given the large roles that risk and uncertainty play in agriculture (Chavas, 2018). In Asia, yields from most crops have increased 100-400% after irrigation (Schoengold and Zilberman, 2007). Stored water can be used also for double cropping of fields.

Despite the increased importance of irrigation, no analysis of international migration controls for it. Coniglio and Pesce (2015) mention the reduced impact anticipated from investing in irrigation and drought-resistant agricultural varieties, without controlling for it. Beine and Parsons (2015) test for the access to natural water sources and find that shortfalls in precipitation constrain migration to developing countries from countries that rely more heavily upon agriculture, and spur movements to developing countries from countries whose groundwater reserves fall below the median of the world groundwater distribution. Access to groundwater is different from being equipped for irrigation, though, which is a more direct measure of adaptation and its use. Other papers on climate-induced migration study particular subpopulations without access to irrigation technology. For example, Jessoe et al. (2017) study traditional or subsistence farmers in rural Mexico who rarely have access to improved seeds or irrigation, and Chort and de la Rupelle (2017) focus on producers in the *ejido* (communal land) sector with non-irrigated land.[4]

The current paper addresses this gap. The relation between climate change, irrigation and migration is obviously difficult since investment in irrigation depends partially on perceptions of climate change. Here, we make a first test of its importance by controlling for whether countries were equipped for irrigation at the start of the period over which migration occurs, thus treating irrigation as pre-existing infrastructure that exists prior to the migration decision. Some studies of internal migration in India indicate a potential importance of irrigation for migration.[5] In an analysis of census data, Dallmann and Millock (2017) find some evidence that Indian states with a higher net rate of irrigation display a smaller rate of migration following drought. At a more disaggregated level, Fishman et al. (2017) studied adaptation to water scarcity among farmers in Gujarat and found a relation between groundwater access and internal migration. In a cross-section analysis using the National Sample Survey of 2007-2008, Zaveri et al. (2018) find that an increase in overall irrigation in the district is associated with a lower probability of temporary migration. In particular, the authors argue that it is access to deep tube wells—which enables better access to groundwater and more effective irrigation—that decreases the probability of temporary migration in their analysis. To the best of our knowledge, however, there is no analysis of international migration that controls for the presence of irrigation as a major means of adaptation to climate change.

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[4] Typically, analyses of the relation between agriculture, migration and climate change in the US exclude all counties west of the 100 degree meridian and the state of Florida, as agriculture in those areas is heavily dependent on subsidized irrigation (Feng et al., 2015).

[5] See also the descriptive analysis in Laube et al. (2012) on farmers using shallow groundwater irrigation for vegetable production in Ghana.

3 Theoretical framework

The theoretical framework is based on a stylized model à la Roy-Borjas that includes the fact that some countries have access to irrigation, I, and others do not. It is hence a model of exogenous irrigation, which is compatible with modeling irrigation as public infrastructure that either exists ($I = 1$) or is not available ($I = 0$) to a farmer making the choice between migrating or not. Irrigation reduces the negative impact of "bad weather" factors.[6] Such bad weather factors are likely multidimensional and could imply higher than optimal temperatures, or lower precipitation, foremost. For simplicity, the model includes only T, and "bad weather" hence means higher temperatures, which are assumed to have a negative impact on agricultural productivity. In the empirical work, both temperature and precipitation are included to avoid omitted variable bias from correlation between the two measures (Auffhammer et al., 2013).

Assume individuals in the origin country (indexed 0) engage in agriculture only. There are two periods, and discounting is disregarded without loss of generality. The wage rate in the country of origin is assumed the same in both periods (as in Cattaneo and Peri (2016)). In the first period, individuals (or "farmers") earn wages w_0:

$$w_0 = \mu_0(T_0, I_0) + \epsilon_0 \tag{1}$$

with ϵ_0 normally distributed with expectation zero and variance σ_0^2.

The expected wage μ_0 is assumed to decrease in temperature $\frac{\partial \mu_0(T_0,I_0)}{\partial T_0} < 0$ but having irrigation reduces the impact compared to not having irrigation: $\frac{\partial \mu_0(T_0,I_0=1)}{\partial T_0} > \frac{\partial \mu_0(T_0,I_0=0)}{\partial T_0}$.

At the beginning of the second period, the farmer decides whether to migrate or not. If

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[6] Irrigation technologies are very diverse and range from traditional spate irrigation to modern high precision drip irrigation systems. Here we will use an indicative irrigation technology indicator, but acknowledge the fact that the technologies have different effectiveness (Vanschoenwinkel and Passel, 2018).

the individual migrates, the wage earned in the destination country (indexed 1) is w_1 which is assumed not to depend on weather (nor irrigation):

$$w_1 = \mu_1 + \epsilon_1 \tag{2}$$

with ϵ_1 normally distributed with expectation zero and variance σ_1^2.

We assume that the expected wage rate is always higher in the destination country, compatible with migration going towards the rich country: $\mu_1 > \mu_0$. An individual migrates if the gains from migration, net of constant migration costs C, exceeds the threshold defined as follows:

$$\epsilon_1 - \epsilon_0 > \mu_0(T_0, I_0) - \mu_1 + C \tag{3}$$

In middle-income countries, which can be defined as countries where individuals are not liquidity constrained, Equation (3) determines migration. Under the assumptions made on the impact of temperature on productivity, it is easy to see that the threshold is decreasing in temperature T, but that the reduction is smaller with irrigation.

The farmer needs to pay for migration up front, though, and this makes for a second constraint, usually referred to as the liquidity constraint (Bazzi, 2017; Kleemans, 2015):

$$\epsilon_0 > C - \mu_0(T_0, I_0) \tag{4}$$

This is the relevant constraint in poor countries (Cattaneo and Peri, 2016). The migration rate in poor countries can hence be defined as

$$1 - \Phi(C - \mu_0(T_0, I_0))$$

where Φ is the cdf of a normal distribution.

Under the reasonable assumption of higher temperatures decreasing agricultural productivity, the threshold defined by the liquidity constraint is increasing in temperature T, and hence reduces the potential to finance a desired migration, in particular international migration which is very costly.[7] Accounting for the potential presence of irrigation, though, reduces the impact of the effect of temperature on agricultural productivity. The reduction in the migration rate would be smaller for poor countries with access to irrigation.

Based on the theoretical framework, we formulate the hypothesis to test on the data:

For poor countries, a worsening in weather factors is associated with a decrease in the emigration rate, but less so if the country has irrigation.

This very simple model has the advantage to allow for a first test of the impact of an important alternative adaptation option—in this case irrigation—at the country level, by simply comparing countries with and without irrigation before the period at which migration occurs. It models irrigation as a public investment that either exists or not in each country. In our empirical analysis, however, we are more flexible, and we allow the effect of irrigation to vary depending on the levels of irrigated area in each country

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[7] On data from Indonesia, Kleemans (2017) estimates about a fourfold difference between the costs of local migration and the costs of international migration.

4 Data

4.1 Migration data

We use data on international migration from Özden et al. (2011), who estimate bilateral migrant stocks between 226 origin and destination countries and territories for each decade between 1960 and 2000. Following Beine and Parsons (2015) and others, we deduce the emigration flow for each country by taking the difference between two consecutive stocks and summing all flows from a specific country. This measure may create negative flows, which could be due to migrants returning home, migrating elsewhere, or dying. We consider negative terms as 0 flow by assuming that this corresponds to migrants who return in their origin country or go to a third destination. Finally, we get the emigration rate for each country and decade by dividing the flow by the total population at the beginning of each decade.

For internal migration, we proxy for rural-urban migration by using urbanization rates. We use data on urbanization rates from the World Urbanization Prospects (UN, 2014). This data set spans 1950 to 2000, with decadal frequency. It provides the proportion of each country's population living in urban areas. It is important to note that our analysis of urbanization rates proxies for rural-urban migration, but does not capture rural-rural migration.

Since we focus the analysis on an agricultural channel and irrigation as adaptation, in particular, we exclude from the sample countries that are fossil fuel dependent. To do so, we use the definition of having a share of fuel exports over GDP above 40% in the year 2000 according to the World Development Indicators.[8] These countries have little cropland, and are less dependent on agriculture in the sense that they have resource rents that enable them to endure agricultural shocks.

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[8] The excluded countries are Gabon, Kuwait, Nigeria, Oman, Qatar, United Arab Emirates and Yemen.

4.2 Irrigation data

We use irrigation data from Siebert et al. (2015), who construct a global data set on the area equipped for irrigation from 1900 to 2005 for 231 countries and territories. Siebert et al. (2015) harmonize data from international databases, including FAOSTAT, Eurostat, and Aquastat, as well as data collected in national surveys, census reports, and statistical yearbooks. Area equipped for irrigation represents irrigation infrastructure and is different from actually irrigated area, which should reduce contemporaneous endogeneity with weather factors. We are interested in the proportion of cropland equipped for irrigation (see Figure 1). To calculate this, we use data on 1970's cropland areas available in 5 arc-minute longitude/latitude grid resolution from the History Database of the Global Environment, HYDE 3.2, produced by Klein Goldewijk and van Drecht (2006).

4.3 Weather data

We use monthly data on average temperature and total precipitation from the University of Delaware (Willmott and Matsuura, 2018). These data are gridded on a 0.5 by 0.5 degree resolution and we use two weighting approaches to aggregate at the country level. In the first method, gridded weather outcomes are weighted and aggregated up to the country level using the Global Population Count Grid Time Series Estimates (GPCGTSE) backcasted gridded population in 1970 as weights (CIESIN, 2017). These weights were developed in CIESIN (2011a) and adjusted to UN population data to give as best an estimate as possible of the population in those years, and should thus give the best measure of past population weights for our purposes. In the second method, gridded weather is aggregated simply using area weights from the Global Rural-Urban Mapping Project (GRUMP) (Balk et al., 2006) version1 (CIESIN, 2011b). Although anomalies[9] are sometimes used in analyses of migration (Marchiori et al., 2012; Beine and Parsons, 2015), we use temperature and precipitation in

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[9] Anomalies are measured as deviations from the long term mean divided by the long term standard deviation.

levels since we focus on the agricultural income channel. Weather variables in levels are better predictors of crop yields, and the level specification is used in other work that links agriculture and migration, including Bohra-Mishra et al. (2014), Mueller et al. (2014), Cai et al. (2016), Cattaneo and Peri (2016) and Jessoe et al. (2017).

Rather than using annual measures of temperature and precipitation, we follow Missirian and Schlenker (2017) and use average temperature and average monthly precipitation during the maize growing season in each origin country. We do this because maize is a staple commodity that is grown in many countries around the world and which provides the highest fraction of human's caloric intake (Roberts and Schlenker, 2013). In addition, maize is more water-intensive than other key staples such as rice, soybeans, and wheat (Brouwer and Heibloem, 1986). We use data on country- and crop-specific growing seasons from Sacks et al. (2010). For countries that are missing data on maize growing season dates, we instead use average monthly temperature and precipitation, based on the entire twelve-month calendar year.

It is important to note that the ideal temperature measure for estimating the impact on crop growth would be to construct daily temperature bins (Schlenker and Roberts, 2009) or to construct degree days (Deschênes and Greenstone, 2007; D'Agostino and Schlenker, 2016). Unfortunately these measures require daily data on temperature and precipitation. Widely used daily gridded weather data sets such as ERA-Interim (Dee et al., 2011) and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker, et al., 2011) span from 1979 to present, corresponding to the modern era of remotely sensed data. These data sets are unfortunately unsuitable for our use since they do not cover the full range of migration data that we use (starting in 1960). Nevertheless, we believe that monthly growing season data is an acceptable substitute, especially as it allows us to exploit the long panel of our migration data.

4.4 Other data

We use cereal yield data from the World Bank (2017). Cereal yield is given as kilograms per hectare of harvested land, and the cereals included are wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains. The GDP per capita data come from the Penn World Table (2009), and the data on the value added in agriculture come from the World Bank (2017).

4.5 Summary statistics

The final sample consists of 105 countries, of which 27 are low-income countries and 78 are middle-income countries. The country names in each group are listed in Appendix A. Table 1 presents summary statistics for the entire set of sample countries, which is all poor and middle-income countries (specifically, the non-OECD countries), excluding the high fuel-exporters. The table is aggregated over all years in the sample and is also disaggregated across the poor versus the middle-income countries. The poor countries in the sample have a lower emigration rate (1.48%) compared to the middle-income countries (2.80%). The average urbanization rate in the poor countries in the sample is 19.3 % compared to 40.4 % in the middle-income countries. The average share of irrigated cropland is 14.9% in the middle-income countries versus 3.45% in the poor countries. Yields are also higher in the middle-income countries. The poor countries have lower precipitation and higher temperatures than the middle-income countries in the sample, on average.

5 Empirical strategy

5.1 Yield regressions

We first demonstrate that higher levels of irrigation mitigate the negative impact of high temperature shocks on yields. To demonstrate this, we regress

$$\begin{aligned} ln(Yield_{it}) = & \beta_1 Temp_{it} + \beta_2 Temp_{it}^2 + \beta_3 Temp_{it} \times Irrig_i + \beta_4 Temp_{it}^2 \times Irrig_i + \\ & \beta_5 Prec_{it} + \beta_6 Prec_{it}^2 + \beta_7 Prec_{it} \times Irrig_i + \beta_8 Prec_{it}^2 \times Irrig_i + \\ & X_{it} + \alpha_i + \phi_{rt} + \epsilon_{it}, \end{aligned} \tag{5}$$

where $Yield_{it}$ is the cereals yield in country i in year t, measured in metric tons of cereal harvested per hectare area planted. $Temp_{it}$ and $Prec_{it}$ are average temperature (C) and precipitation (100 mm/month) during the maize growing season, both from University of Delaware, using either population weights or area weights. $Irrig_i$ is the share of 1970's crop land that was equipped for irrigation. We use 1970's irrigation levels instead of contemporaneous irrigation levels to reduce endogeneity. The term X_{it} represents controls for 1970's GDP per capita interacted with temperature and precipitation and their squares. This term is included to verify that it is truly irrigation levels (and not the general level of development) that influence the temperature-yield relationship. The term α_i is a country fixed effect that accounts for time-invariant factors that affect crop yields and ϕ_{rt} represents a region-specific quadratic time trend that controls for changes over time. Standard errors are clustered at country level. The yield regression spans 1961 to 2016, with some missing observations. The regression is restricted to poor and middle-income countries that are not high fuel-exporters.

5.2 Migration regressions: Fixed effects approach

Next, we explore the relationships between temperature, income, irrigation and migration. To begin, we follow Cattaneo and Peri (2016) and estimate

$$\begin{aligned} ln(Migr_{it}) = & \sum_{j=1}^{4} \gamma_{1j} Income_{ij} \times Temp_{it} + \sum_{j=1}^{4} \gamma_{2j} Income_{ij} \times Prec_{it} + \\ & \alpha_i + \phi_{r,t} + \phi_{p,t} + \epsilon_{it} \end{aligned} \tag{6}$$

where $Migr_{it}$ is either the emigration rate from the previous decade, or the urbanization rate in the previous decade. The variables $Temp_{it}$ and $Prec_{it}$ are the averages of temperature and precipitation, respectively, during the maize growing season in the origin country, over the previous decade. $Income_{ij}$ is a dummy that equals one if country i is in the jth income quartile (based on 1990's GDP per capita). The term $\phi_{r,t}$ represents a set of decade-by-region dummies that absorb regional factors related to migration that may be varying over time. The term $\phi_{p,t}$ represents decade fixed effects interacted with the poor country dummy, to capture whether migration may be changing differently over time for poor countries as compared to middle-income countries. We cluster the regression at the country level. Following Cattaneo and Peri (2016), we expect to find evidence of a poverty trap: higher temperatures reduce emigration from poor countries.

Next, we integrate irrigation into our analysis. We estimate

$$\begin{aligned} ln(Migr_{it}) =& \delta_1 Temp_{it} + \delta_2 Temp_{it} \times Poor_i + \delta_3 Temp_{it} \times Poor_i \times Irrig_i + \\ & \delta_4 Prec_{it} + \delta_5 Prec_{it} \times Poor_i + \delta_6 Prec_{it} \times Poor_i \times Irrig_i + \\ & \alpha_i + \phi_{r,t} + \phi_{p,t} + \epsilon_{it} \end{aligned} \tag{7}$$

where $Poor_i$ is a dummy for whether a country's GDP per capita is in the bottom quartile of the distribution in 1990 and $Irrig_i$ is the country's proportion of irrigated crop land in 1970. As above, the regression includes country fixed effects, region-by-decade dummies, and poor-by-decade dummies. We expect to find $\delta_2 < 0$: higher temperatures reduce migration in poor countries. We also expect to find $\delta_3 > 0$: having high levels of irrigation offsets the negative impact of high temperatures on migration.

6 Results

6.1 Yield regression results

Before exploring the impact of irrigation on migration, we first demonstrate that irrigation modifies the impact of weather on yields. The results of our yield regressions are shown in Table A1 in the Appendix. We focus on the interaction coefficients between temperature and irrigation, because these are the results that are important for our subsequent migration analysis. Columns (1) and (3) present a linear yield specification, with population and area weights respectively. In these columns, we see a positive interaction coefficient between temperature and irrigation— irrigation access offsets the negative impacts of higher temperatures on yields—but the coefficient is not statistically significant. However this lack of precision may be driven by the fact that temperature has nonlinear yield effects.

To explore this effect, in Columns (2) and (4) we add quadratic terms of temperature and precipitation, and also interact these terms with irrigation. In this specification, we find highly significant interaction terms between temperature and irrigation. We find that higher levels of irrigation reduce the negative effect of temperature on yields, but also that this effect is concave, and diminishes as temperatures rise even higher (due to the quadratic temperature term). In terms of magnitudes, if we compare a country with the mean level of irrigation in 1970 (across all countries) to a country that is one standard deviation above this mean, the reduction in yields from a 1° C increase in temperature will be 68% lower for the country with the higher level of irrigation. Focussing on poor countries only, and comparing a country with the mean level of irrigation in 1970 (across all poor countries) to a country that is one standard deviation above this mean, the decrease in yields from a 1° C increase in temperature will be 12% lower for the country with the higher level of irrigation.[10] Lastly, it is important to note that all columns of Table A1 include controls for 1970's GDP per capita interacted with the weather variables, to ensure that our irrigation measure is truly capturing the impact of irrigation, rather than the general level of development in the country.

6.2 Migration regressions, main results

Having confirmed the ex ante hypothesis of the impact of irrigation on agricultural productivity, we present the results for migration. In these estimations, we always rely on the population-weighted estimates for interpreting the effects, since the relevant weather for migration incentives should be the weather experienced by the population in a given area (Dell

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[10] These calculations are done assuming a 1°C increase in temperatures, from the sample mean, and using the coefficients from Column (2).

et al., 2014). For comparison with the literature, Table 2 replicates the results of Cattaneo and Peri (2016), showing that higher temperatures are associated with a decrease in emigration rates from the poorest countries in the world, whereas no such effect is found for countries in the three upper quartiles of the distribution of GDP per capita in 1990 levels. A 1° C increase in temperatures leads to a 68% reduction in emigration from countries in the bottom quartile (column (1)), an estimate that is comparable to estimates from Cattaneo and Peri (2016). Precipitation does not have a significant effect on long-term rates of emigration, as in Cattaneo and Peri (2016) and other analyses of international migration (Beine and Parsons, 2015; Cai et al., 2016).

Higher temperatures are also weakly associated with a lower rate of urbanization in poorer countries, but the effect is either not statistically significant (population-weighted weather data) or significant at only the 10% level (area-weighted weather data). In terms of magnitudes, and looking at column (4), a 1°C increase in temperatures leads to a 5.7 percentage point reduction in the urbanization share for countries in the bottom quartile. Contrary to the case of emigration, precipitation levels are also significantly associated with the level of urbanization. For countries in the second quartile of the GDP per capita distribution in 1990, lower urbanization rates are associated with lower precipitation levels. In the poorest countries of the world, though, low urbanization rates are associated with higher precipitation levels, contrary to ex ante hypotheses on urbanization (Henderson et al., 2017). This may come from the level of aggregation, since the same effect of precipitation is found also in Cattaneo and Peri (2016). Hossain and Ahsan (2018) show the importance of spatial spillovers when studying phenomena at a subnational level such as rural-urban migration.

The main results of the effect of irrigation on emigration are presented in Table 3. As in Cattaneo and Peri (2016), temperature does not have a statistically significant effect on migration if we look at the set of poor and middle income countries together (columns (1) and (4)). However, once we include an interaction term between temperature and the poor country dummy, we find a large, negative, and statistically significant effect of temperatures on emigration rates. As in Cattaneo and Peri (2016), this is the climate-migration poverty trap effect: higher temperatures reduce incomes in poor countries, blocking the ability of individuals to migrate. Turning to our main result of interest—the extent to which access to irrigation modulates this effect— we look at columns (3) and (6) where we include the triple interaction of temperature, poor country dummy, and 1970's irrigation. This triple interaction term captures the differential effect that temperature has on migration for a poor country with comparatively lower or higher levels of irrigation.

We find that access to irrigation offsets the climate-migration poverty trap effect and the coefficient is significant at a 1% level when using population weights for country weather averages (column (3)). Using area weights, in column (6), we still estimate a large positive coefficient for the effect of irrigation, but it is not statistically significant. In terms of magnitudes, and using the coefficients in column (3), we find that a 1°C increase in decadal average temperatures leads to a 71% reduction in emigration poor countries with the mean level of irrigation in 1970. For poor countries that are one standard deviation above the mean irrigation in 1970, we only see a 44% reduction in emigration.[11] Thus, this level of irrigation reduces the impact of high temperatures on emigration by 38%.

The results for urbanization rates in Table 4 confirm the effects of irrigation: poor countries with irrigation display a much smaller negative response to higher temperatures. For poor countries who had the mean level of irrigation in 1970, a 1°C increase in decadal average temperatures leads to a 4.7 percentage points reduction in urbanization. For poor countries which were one standard deviation above the mean level of irrigation in 1970, we only see a 1.1 percentage points reduction in urbanization, equivalent to a reduction in magnitude of the effect by 77%. For urbanization, which we use as a proxy for rural-urban migration, the interaction effect of irrigation is also significant for precipitation where it decreases the negative relation between precipitation and urbanization for the poor countries. The estimations of the urbanization rate explain much more of the variability in observed rates than for

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[11] These effects are estimated using the coefficient estimates from the first three rows of column (3) in Table 3, and multiplying them by the appropriate values of 1970's irrigation.

international migration, with an adjusted R^2 above 0.7 compared to 0.15 for the estimations of emigration. In part, this could be a direct effect of the bigger sample since another decade of urbanization data exists which increases the sample size.

6.3 Migration regressions, robustness checks

We now explore the robustness of our results to some changes in specification.

In our first robustness check, we consider how irrigation influences migration for countries that rely heavily on agriculture. Following Cattaneo and Peri (2016), we define agricultural countries to be those countries in the top quartile of agricultural value added as a share of GDP. While many of our poor countries also count as agricultural countries, the two sets are not identical. We introduce additional interaction effects into our regression to tease out the effects of irrigation for countries that could be agricultural, poor, or both. We would expect access to irrigation to matter most strongly for agricultural countries. We would also expect irrigation to matter for poor countries, to the extent that these countries also rely in part on agriculture (they just may not be in the top quartile in terms of their dependence).

The results in Table 5 show, as in Cattaneo and Peri (2016), that higher temperatures have a negative effect on emigration both for poor countries and agricultural countries, where an agricultural country is defined as a country in the top quartile of agricultural value added as a share of GDP. The cushioning effect of irrigation, though, is significant only for agricultural countries (columns (3) and (6)). It is important to note, however, that the sign for the triple interaction on temperature, poor country and irrigation is positive, although not statistically significant. This is perhaps unsurprising since the poor variable and the agricultural country variable are quite collinear. As before, precipitation never has a statistically significant effect on emigration. The results on rural-urban migration, as proxied by the country's urbanization rate, confirm these results (Table 6). Urbanization rates are lower with higher temperatures, and access to irrigation dampens the effect, but only for agricultural countries. Also, the counter-intuitive negative relation between precipitation and urbanization rates only holds for poor countries and is not found in agricultural countries (columns (2) and (5)). Taken together, we take Tables 5 and 6 as strengthening our evidence for the protective role of irrigation, because these tables show that we find a protective effect of irrigation, whether we focus on poor countries or on agricultural countries.

Next, we show that the effects of irrigation on migration rates is robust to measuring access to irrigation using a dummy variable. In our main specification, we use the proportion of 1970's cropland equipped for irrigation in each country as our measure of irrigation. In this robustness test, we instead define irrigation as a dummy, whereby a country is considered to be a "high irrigation" country if it was above some threshold for irrigation (across the set of poor and middle income countries) in 1970. Table 7 presents the results of this robustness check for emigration, where we vary the threshold for high irrigation to be either above the median share of irrigated cropland in 1970, or above either the 40th or the 60th percentile. The sign of the main results still holds: higher temperatures reduce emigration in poor countries, and higher levels of irrigation attenuates this effect. In terms of statistical significance, the effect of irrigation is significant if we use the median as the threshold (population or area weights) or the 60th percentile (population weights). For the 40th percentile, the triple interaction coefficient is positive, but not significant. Table 8 confirms the robustness of the results for urbanization using the same various thresholds for irrigation. In this case, the results are even stronger, and we find evidence that irrigation has a statistically significant protective effect on migration in all columns, e.g., with all weighting methods and with all different threshold definitions.

7 Discussion

In our analysis and discussion, we have emphasized the agricultural channel for our results: higher temperatures reduce agricultural incomes which, combined with liquidity constraints, reduces migration in poor countries. However, it is important to note that higher temperatures affect many outcomes, including, but not limited to, conflict (Hsiang et al., 2013; Burke et al., 2015), mortality (Deschênes and Greenstone, 2011), health (Deschênes, 2014), labor productivity (Zivin and Neidell, 2014; Somanathan et al., 2015) and industrial total factor productivity (Zhang et al., 2018). Each of these items may, in turn, itself affect migration (see for example Deschênes and Moretti (2009)). In our (reduced form) regressions, it is important to note that our coefficient for the impact of temperature on migration is not limited to the agricultural channel, but, in fact, includes the total effect of temperature on migration, which may include all of these other pieces. However, it is not desirable to control for these other channels, due to the "bad control' problem described in Angrist and Pischke (2008). On the other hand, in this paper our main outcome of interest is the modulating role of irrigation. In this case, it is clear that irrigation affects agricultural incomes directly. Furthermore, irrigation either does not affect the other factors listed above, or, only affects them via the channel of agricultural incomes. For this reason, we feel confident interpreting the agricultural channel to be the mechanism that is driving our irrigation results.

Despite the robustness checks we have run, there are still some important limitations to note about our analysis. First, while the analysis of international migration necessarily involves the use of cross-country data sets, an associated limitation of this is that attributes such as weather must be aggregated to the country level, which may obscure a lot of variation and heterogeneity. This is particularly important for precipitation, which follows localized regional patterns and is less spatially homogenous than temperature. Therefore, we do not emphasize the results for precipitation in the analysis. Future work should study international and internal migration, using detailed single-country data sets, to test whether the broad patterns we have uncovered here, at the international level, also hold when using more disaggregated weather data at the sub-country level. Daily weather data exist at such a level of analysis, which would allow for better measures of the non-linearities in the weather-crop relation. Disaggregated data are also likely to allow for a better understanding of the effects of precipitation (Hossain and Ahsan, 2018).

Second, studies at the country level would allow for analyzing further the impact of irrigation on internal migration, which is comprised of both rural-urban and rural-rural migration. Our analysis in the current paper uses urbanization rates to proxy for rural-urban migration, due to limited coverage on internal migration flows for an international panel of countries. Hence the current analysis does not capture the effects of irrigation on rural-rural migration. The use of macro migration flows also precludes an analysis of the differences in response that we find between international and rural-urban migration. The effects of irrigation may differ according to the characteristics of migrants. If international migration is selected on wealthier individuals, who are large landowners typically, and who can decide on irrigation investments, rural-urban migration may concern poorer landless individuals possibly. Such an analysis of a heterogeneous impact according to categories of individuals is an important topic to explore in future research using specific country data that would allow to study the micro-economic incentives in more detail.

Another limitation of our study is that we take irrigation as an exogenous, given factor, and do not account for irrigation investments that are likely to occur simultaneously with, and because of, climate change. Irrigation systems are typically capital intensive and the equipment has a long life-time. There is also considerable inertia in irrigation investments (McKinsey and Evenson, 1999), which may justify our treatment of irrigation as a fixed infrastructure. Ongoing work aims at disentangling the relation between weather factors, irrigation investments, and migration.

Finally, whereas irrigation has proven benefits in the short run as an adaptation measure to shield yields from climate change, it can also change crop choices in the long run and induce farmers to plant more water-intensive crops, and thus increase the weather sensitivity of agriculture (Hornbeck and Keskin, 2014; Damania et al., 2017). Damania et al. (2017) refers to this as an example of maladaptation in agriculture which could amplify the impact of future shocks. An analysis of this consequence of irrigation was out of scope of the current analysis, particularly because of lack of international data on planted crop area in panel format. This is a topic for future research that could be studied best using disaggregated country-level data.

Irrigation as long term adaptation for climate change impacts also raises issues on its own because of its effect on global water demand (Haddeland et al., 2014). Haddeland et al. (2014) projects irrigation water to become even more scarce in the future in already irrigated areas of southern and eastern Asia. Similarly, Zaveri et al. (2016) project that groundwater demand in India will grow under climate change. The social losses due to water overuse, in particular over extraction of groundwater, have been estimated to be substantial (Sayre and Taraz, 2019). The present analysis should therefore not be interpreted in a normative manner, but only as a positive analysis on how accounting for irrigation as a potential adaptation option in agriculture affects migration induced by changes in weather.

8 Conclusion

The acceleration of climate change necessitates that the sustainable development community address the issue of climate change—and how it threatens development—head on. A key piece of this work is understanding how households in low- and middle-income countries will be able to adapt to climate-related hazards. And, when looking at adaptations, it is important to not only consider adaptive behaviors in isolation, but also to consider interactions between different adaptive behaviors.

In this paper, we have explored the effect of increased temperatures on international migration and urbanization rates and examined the role of irrigation access in shaping these relationships. Using a global data set of low- and middle-income countries, we have demonstrated that—at least for the current temporal and geographic sample—higher levels of irrigation mitigate the negative impact of high temperatures on yields. Furthermore, we have shown that this agricultural relationship spills over on to the climate–migration relationship. Specifically, we find that higher temperatures reduce international and rural-urban migration in poor countries, but that access to irrigation offsets this effect. Our results are robust to two important variations in specification: to focusing on agricultural countries, instead of poor countries; and to measuring irrigation as a dummy variable, rather than in levels.

Our results suggest several fruitful pathways for future research. First, as described in Section 7, since the current study takes the country as the unit of analysis, we are only partially able to address the endogeneity of irrigation, and we are not really able to analyze how irrigation and migration together coevolve in response to changes in climate. It would be valuable for future work to focus on a single country, and take sub-national units as the unit of analysis, so as to be better able to explore these coevolving changes together. Such work could better address all the institutional factors affecting farmers' choices at the household and the community level (McCord et al., 2018; Burnham et al., 2018) as well as explore nuanced issues around the formation of poverty traps (Barrett et al., 2018). It is also possible that a global gridded migration data set, that analyzed migration outcomes at the grid point, might also be able to tackle this issue and provide insight.

More broadly, we approached this question because it seemed clear that agriculture is an important driver behind the climate-migration relationship and because irrigation seemed an important factor that had been heretofore overlooked. However, in reality there is a broad web of adaptations available in response to changes in climate, not merely just irrigation and migration, and it seems critical for the next wave of climate change adaptation research to either consider these adaptations more holistically or, at the very least, to consider the interactions of key pairs of them. Relatively little work has been done in this area, and hence it seems to be a fruitful area for future research.

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Figure 1: Maps of area equipped for irrigation in 1970

Note: Data source: Siebert et al. (2015).

Table 1: Summary statistics for poor and middle-income countries.

	Full Sample	Middle-Income	Poor
Emigration rate (emigration flow/population)	0.0246	0.0280	0.0148
	(0.0396)	(0.0445)	(0.0167)
Share of urban population	0.350	0.404	0.193
	(0.209)	(0.207)	(0.114)
Share of 1970 cropland irrigated	0.120	0.149	0.0345
	(0.190)	(0.209)	(0.0670)
Land under cereal production, million hectares	3.857	4.670	1.492
	(13.74)	(15.82)	(1.644)
Cereal production, million metric tons	8.366	10.76	1.403
	(37.52)	(43.24)	(1.472)
Cereal yield, metric tons per hectare	1.681	1.900	1.042
	(1.266)	(1.377)	(0.450)
Real GDP per capita, 2011 USD	4308.1	5410.2	1238.5
	(7153.8)	(8053.7)	(606.6)
Temperature, C, population weights	23.50	23.29	24.13
	(4.182)	(4.057)	(4.487)
Temperature, C, area weights	23.75	23.50	24.50
	(4.277)	(4.206)	(4.413)
Precipitation, 100mm/month, population weights	1.366	1.402	1.259
	(0.876)	(0.959)	(0.552)
Precipitation, 100mm/month, area weights	1.361	1.404	1.235
	(0.916)	(0.989)	(0.637)
Observations	525	390	135

Note: Mean coefficients. Standard deviations in parentheses. Our sample consist of 105 poor and middle-income countries. The table presents averages of each variable for each decade that the variable is available. The temperature and precipitation values are monthly averages for the maize growing season in each country.

Table 2: Temperature effects on emigration and urbanization for different income quartiles.

	(1) Emigration(pop-wgts)	(2) Emigration(area-wgts)	(3) Urbanization(pop-wgts)	(4) Urbanization(area-wgts)
Quartile=1 * Temperature	-1.129**	-1.478**	-0.0449	-0.0568*
	(0.562)	(0.589)	(0.0281)	(0.0304)
Quartile=2 * Temperature	0.887**	0.644	0.0132	0.00398
	(0.445)	(0.477)	(0.0308)	(0.0288)
Quartile=3 * Temperature	0.368	0.104	0.0177	0.0143
	(0.295)	(0.330)	(0.0182)	(0.0200)
Quartile=4 * Temperature	0.327	0.0969	0.0317	0.0268
	(0.389)	(0.391)	(0.0412)	(0.0424)
Quartile=1 * Precipitation	-0.848	-0.852	-0.114**	-0.137***
	(0.771)	(0.862)	(0.0441)	(0.0462)
Quartile=2 * Precipitation	0.0698	0.219	0.0554**	0.0619**
	(0.675)	(0.723)	(0.0279)	(0.0284)
Quartile=3 * Precipitation	-0.0826	-0.518	-0.0240	-0.0356
	(0.355)	(0.399)	(0.0339)	(0.0394)
Quartile=4 * Precipitation	0.147	0.912	-0.0609	-0.143
	(1.013)	(1.608)	(0.0797)	(0.0905)
Observations	412	412	510	510
R^2	0.224	0.221	0.783	0.786
Adjusted R^2	0.171	0.168	0.769	0.772

Note: Standard errors in parentheses. Years 1960-2000. Sample is 105 poor and middle-income countries. Dependent variable is log emigration rate (Columns 1 & 2) or urban population share (Columns 3 & 4). Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL. Country fixed effects, decade-by-region fixed effects, decade-by-poor fixed effects. Standard errors clustered at country level. Income quartiles are based on the set of poor and middle-income countries, using 1990 data on GDP per capita.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Temperature, income, irrigation, and emigration.

	(1) Pop-weights	(2) Pop-weights	(3) Pop-weights	(4) Area-weights	(5) Area-weights	(6) Area-weights
Temperature	0.242	0.482*	0.457*	-0.00391	0.229	0.212
	(0.235)	(0.249)	(0.249)	(0.258)	(0.275)	(0.278)
Poor=1 * Temperature		-1.619***	-2.027***		-1.709***	-1.921***
		(0.594)	(0.611)		(0.636)	(0.687)
Poor=1 * Temperature * 1970 irrig			9.654***			6.298
			(3.675)			(4.144)
Precipitation	-0.158	-0.0236	-0.0199	-0.212	-0.0842	-0.0848
	(0.355)	(0.378)	(0.378)	(0.400)	(0.444)	(0.444)
Poor=1 * Precipitation		-0.839	-1.292		-0.764	-1.050
		(0.846)	(0.993)		(0.960)	(1.126)
Poor=1 * Precipitation * 1970 irrig			7.714			3.663
			(26.53)			(30.84)
Observations	412	412	412	412	412	412
R^2	0.198	0.219	0.229	0.195	0.214	0.218
Adjusted R^2	0.157	0.175	0.181	0.153	0.169	0.169

Note: Standard errors in parentheses. Years 1960-2000. Sample is 105 poor and middle-income countries. The dependent variable is the natural logarithm of emigration rates. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL. Country fixed effects, decade-by-region fixed effects, decade-by-poor fixed effects. Standard errors clustered at country level. Poor countries are in the lowest GDP per capita quartile, based on 1990 data and non-OECD countries. Irrigation is the fraction of cropland equipped for irrigation in 1970.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Temperature, income, irrigation, and urbanization.

	(1) Pop-weights	(2) Pop-weights	(3) Pop-weights	(4) Area-weights	(5) Area-weights	(6) Area-weights
Temperature	0.00864	0.0209	0.0206	0.00263	0.0156	0.0147
	(0.0158)	(0.0179)	(0.0179)	(0.0190)	(0.0212)	(0.0211)
Poor=1 * Temperature		-0.0652*	-0.0865**		-0.0715*	-0.0867**
		(0.0337)	(0.0346)		(0.0375)	(0.0379)
Poor=1 * Temperature * 1970 irrig			0.537**			0.464
			(0.250)			(0.290)
Precipitation	-0.0269	0.00906	0.00893	-0.0420	-0.000768	-0.000475
	(0.0275)	(0.0259)	(0.0259)	(0.0290)	(0.0268)	(0.0269)
Poor=1 * Precipitation		-0.123**	-0.171***		-0.137**	-0.186***
		(0.0511)	(0.0521)		(0.0533)	(0.0534)
Poor=1 * Precipitation * 1970 irrig			1.847**			1.838*
			(0.811)			(0.953)
Observations	510	510	510	510	510	510
R^2	0.774	0.780	0.783	0.775	0.781	0.783
Adjusted R^2	0.762	0.767	0.769	0.763	0.768	0.769

Note: Standard errors in parentheses. Years 1960-2000. Sample is 105 poor and middle-income countries. The dependent variable is the urban population share. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL. Country fixed effects, decade-by-region fixed effects, decade-by-poor fixed effects. Standard errors clustered at country level. Poor countries are in the lowest GDP per capita quartile, based on 1990 data and non-OECD countries. Irrigation is the fraction of cropland equipped for irrigation in 1970.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Temperature, income, irrigation, emigration, and agricultural status.

	(1) Pop-weights	(2) Pop-weights	(3) Pop-weights	(4) Area-weights	(5) Area-weights	(6) Area-weights
Temperature	0.360	0.358	0.465*	0.134	0.135	0.244
	(0.261)	(0.261)	(0.278)	(0.277)	(0.278)	(0.295)
Agri=1 * Temperature	-1.661***	-1.911***	-1.529***	-1.751***	-1.970***	-1.686***
	(0.498)	(0.524)	(0.519)	(0.483)	(0.499)	(0.495)
Agri=1 * Temperature * 1970 irrig		14.25**	15.83***		13.84**	13.87***
		(6.543)	(5.146)		(5.520)	(4.779)
Poor=1 * Temperature			-1.179**			-1.152**
			(0.561)			(0.557)
Poor=1 * Temperature * 1970 irrig			4.589			3.412
			(4.438)			(3.901)
Precipitation	0.352	0.357	0.264	0.370	0.373	0.294
	(0.406)	(0.406)	(0.406)	(0.474)	(0.475)	(0.479)
Agri=1 * Precipitation	-2.245***	-2.464***	-1.609**	-2.378**	-2.626***	-1.743**
	(0.827)	(0.811)	(0.672)	(0.951)	(0.895)	(0.764)
Agri=1 * Precipitation * 1970 irrig		12.45	-51.02**		14.17	-84.70***
		(33.34)	(25.10)		(36.70)	(30.39)
Poor=1 * Precipitation			-1.737			-1.629
			(1.131)			(1.382)
Poor=1 * Precipitation * 1970 irrig			93.31***			124.2***
			(28.20)			(33.82)
Observations	376	376	376	376	376	376
R^2	0.232	0.236	0.256	0.232	0.236	0.256
Adjusted R^2	0.184	0.184	0.196	0.184	0.183	0.196

Note: Standard errors in parentheses, clustered at country level. Years 1960-2000. Sample is 105 poor and middle-income countries. The dependent variable is the natural logarithm of emigration rates. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL. Poor countries are in the lowest GDP per capita quartile, based on 1990 data and non-OECD countries. Agricultural countries are countries in the top quartile of agricultural value added as a share of GDP. Irrigation is the fraction of cropland equipped for irrigation in 1970.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Temperature, income, irrigation, urbanization, and agricultural status.

	(1) Pop-weights	(2) Pop-weights	(3) Pop-weights	(4) Area-weights	(5) Area-weights	(6) Area-weights
Temperature	0.0248	0.0237	0.0280	0.0109	0.00977	0.0145
	(0.0200)	(0.0200)	(0.0197)	(0.0235)	(0.0235)	(0.0236)
Agri=1 * Temperature	-0.0588*	-0.0849**	-0.0383	-0.0561	-0.0818**	-0.0359
	(0.0327)	(0.0341)	(0.0470)	(0.0356)	(0.0364)	(0.0442)
Agri=1 * Temperature * 1970 irrig		0.759**	0.875*		0.886***	0.966**
		(0.300)	(0.444)		(0.313)	(0.439)
Poor=1 * Temperature			-0.0894			-0.0946*
			(0.0573)			(0.0510)
Poor=1 * Temperature * 1970 irrig			0.267			0.317
			(0.462)			(0.406)
Precipitation	-0.00990	-0.00830	-0.00641	-0.0228	-0.0209	-0.0168
	(0.0264)	(0.0266)	(0.0272)	(0.0279)	(0.0280)	(0.0286)
Agri=1 * Precipitation	-0.0225	-0.0476	0.0461	-0.0237	-0.0512	0.0491
	(0.0566)	(0.0910)	(0.0560)	(0.0646)	(0.105)	(0.0641)
Agri=1 * Precipitation * 1970 irrig		0.901	0.583		1.071	0.756
		(1.683)	(1.021)		(1.846)	(1.244)
Poor=1 * Precipitation			-0.209*			-0.244*
			(0.121)			(0.129)
Poor=1 * Precipitation * 1970 irrig			2.192			2.498
			(1.621)			(1.814)
Observations	465	465	465	465	465	465
R^2	0.772	0.775	0.779	0.771	0.774	0.779
Adjusted R^2	0.757	0.759	0.762	0.757	0.759	0.762

Note: Standard errors in parentheses. Years 1960-2000. Sample is 105 poor and middle-income countries. The dependent variable is the urban population share. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL. Country fixed effects, decade-by-region fixed effects, decade-by-poor fixed effects. Standard errors clustered at country level. Poor countries are in the lowest GDP per capita quartile, based on 1990 data and non-OECD countries. Agricultural countries are countries in the top quartile of agricultural value added as a share of GDP. Irrigation is the fraction of cropland equipped for irrigation in 1970.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Temperature, irrigation, and emigration with different thresholds for high irrigation.

	(1) Pop-50	(2) Pop-40	(3) Pop-60	(4) Area-50	(5) Area-40	(6) Area-60
Temperature	0.467*	0.480*	0.470*	0.217	0.228	0.221
	(0.249)	(0.249)	(0.249)	(0.276)	(0.276)	(0.276)
Poor=1 * Temperature	-1.957***	-1.884***	-1.891***	-1.947***	-1.866***	-1.876***
	(0.598)	(0.616)	(0.589)	(0.674)	(0.695)	(0.661)
Poor=1 * High irrigation=1 * Temperature	1.596**	0.941	1.512**	1.286**	0.561	1.032
	(0.670)	(0.698)	(0.761)	(0.615)	(0.660)	(0.706)
Precipitation	-0.0238	-0.0196	-0.0206	-0.0871	-0.0831	-0.0820
	(0.378)	(0.379)	(0.378)	(0.444)	(0.445)	(0.444)
Poor=1 * Precipitation	-1.591*	-1.395	-1.096	-1.581	-1.158	-0.928
	(0.861)	(1.008)	(0.887)	(1.063)	(1.087)	(1.005)
Poor=1 * High irrigation=1 * Precipitation	2.610***	1.292	0.0369	2.533***	0.966	-2.707
	(0.732)	(1.274)	(5.621)	(0.922)	(1.494)	(8.179)
Observations	412	412	412	412	412	412
R^2	0.229	0.223	0.226	0.221	0.215	0.219
Adjusted R^2	0.181	0.174	0.178	0.173	0.167	0.170

Note: Standard errors in parentheses. Years 1960-2000. Sample is 105 poor and middle-income countries. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL. Country fixed effects, decade-by-region fixed effects, decade-by-poor fixed effects. Standard errors clustered at country level. Poor countries are in the lowest GDP per capita quartile, based on 1990 data and non-OECD countries. High irrigation countries are above the 50th, 40th, or 60th percentile for proportion of area equipped for irrigation in 1970, depending on the column of the table.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Temperature, irrigation, and urbanization with different thresholds for high irrigation.

	(1) Pop-50	(2) Pop-40	(3) Pop-60	(4) Area-50	(5) Area-40	(6) Area-60
Temperature	0.0205	0.0212	0.0207	0.0148	0.0155	0.0151
	(0.0179)	(0.0179)	(0.0179)	(0.0212)	(0.0212)	(0.0212)
Poor=1 * Temperature	-0.0912***	-0.0951***	-0.0811**	-0.0926**	-0.0998***	-0.0835**
	(0.0325)	(0.0326)	(0.0338)	(0.0356)	(0.0360)	(0.0368)
Poor=1 * High irrigation=1 * Temperature	0.0956***	0.0956***	0.0764**	0.0954***	0.0940***	0.0662*
	(0.0292)	(0.0279)	(0.0297)	(0.0328)	(0.0299)	(0.0352)
Precipitation	0.00905	0.00958	0.00902	-0.000652	-0.000178	-0.000597
	(0.0260)	(0.0259)	(0.0260)	(0.0270)	(0.0268)	(0.0269)
Poor=1 * Precipitation	-0.158***	-0.188***	-0.135**	-0.185***	-0.204***	-0.148***
	(0.0513)	(0.0458)	(0.0519)	(0.0497)	(0.0478)	(0.0543)
Poor=1 * High irrigation=1 * Precipitation	0.142***	0.199***	0.162*	0.171***	0.210***	0.113
	(0.0440)	(0.0463)	(0.0871)	(0.0448)	(0.0497)	(0.155)
Observations	510	510	510	510	510	510
R^2	0.783	0.785	0.781	0.784	0.785	0.782
Adjusted R^2	0.770	0.771	0.768	0.771	0.772	0.768

Note: Standard errors in parentheses. Years 1960-2000. Sample is 105 poor and middle-income countries. The dependent variable is the urban population share. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL. Country fixed effects, decade-by-region fixed effects, decade-by-poor fixed effects. Standard errors clustered at country level. Poor countries are in the lowest GDP per capita quartile, based on 1990 data and non-OECD countries. High irrigation countries are above the 50th, 40th, or 60th percentile for proportion of area equipped for irrigation in 1970.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

A Appendix: List of countries in the sample

A.1 List of poor countries (27)

Afghanistan, Benin, Burkina Faso, Burundi, Cambodia, Central African Republic, Congo (DRC), Equatorial Guinea, Ethiopia, Gambia, Ghana, Guinea-Bissau, Lao People's Democratic Republic, Lesotho, Liberia, Madagascar, Malawi, Mali, Mozambique, Niger, Rwanda, Somalia, Sudan, Tanzania, Togo, Uganda and Zambia.

A.2 List of middle-income countries (78)

Albania, Algeria, Angola, Argentina, Bahamas, Bangladesh, Belize, Bhutan, Bolivia, Botswana, Brazil, Brunei Darussalam, Bulgaria, Cape Verde, Cameroon, Chad, China, Colombia, Comoros, Costa Rica, Cote d'Ivoire, Cuba, Cyprus, Djibouti, Dominican Republic, Ecuador, Egypt, El Salvador, Fiji, Guatemala, Guinea, Guyana, Haiti, Honduras, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Kenya, Lebanon, Libya, Malaysia, Mauritania, Mauritius, Morocco, Namibia, Nepal, Nicaragua, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Romania, Russian Federation, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Sierra Leone, Solomon Islands, South Africa, Sri Lanka, Saint Vincent and the Grenadines, Suriname, Swaziland, Syrian Arab Republic, Thailand, Trinidad and Tobago, Tunisia, Uruguay, Vanuatu, Venezuela, Vietnam and Zimbabwe.

B Appendix: Robustness Tables

Table A1: Temperature, irrigation, and crop yields.

	(1) Population-weights	(2) Population-weights	(3) Area-weights	(4) Area-weights
Temperature	-0.0422	-0.238	-0.0395	-0.271
	(0.0307)	(0.183)	(0.0310)	(0.174)
Temperature * Temperature		0.00416		0.00476
		(0.00378)		(0.00353)
1970 irrig * Temperature	0.0420	0.950^{**}	0.0821	1.361^{***}
	(0.0846)	(0.457)	(0.0819)	(0.440)
1970 irrig * Temperature * Temperature		-0.0187^{**}		-0.0252^{***}
		(0.00922)		(0.00849)
Precipitation	0.120^{***}	0.329^{***}	0.132^{***}	0.339^{***}
	(0.0317)	(0.112)	(0.0341)	(0.123)
Precipitation * Precipitation		-0.0451^{*}		-0.0418
		(0.0261)		(0.0266)
1970 irrig * Precipitation	-0.215^{*}	0.0732	-0.198	0.667
	(0.116)	(0.300)	(0.142)	(0.409)
1970 irrig * Precipitation * Precipitation		-0.161		-0.352^{***}
		(0.106)		(0.132)
Observations	5002	5002	5002	5002
R^2	0.431	0.438	0.431	0.437
Adjusted R^2	0.429	0.435	0.429	0.435

Note: Standard errors in parentheses. Years 1961-2016. Sample is 105 poor and middle-income countries. The dependent variable is yield in tons of cereal harvested per hectare planted. Country fixed effects. Region-specific quadratic time trends. Standard errors clustered at country level. Average temperature (C) & precipitations (100 mm/month) during maize growing season are from UDEL weather data. Y1970's irrigation is the share of 1970's crop land irrigated. All columns control for 1970's GDP per capita, interacted with temperature and precipitation terms.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$