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**Abstract**

Climate change will affect both international and internal migration. Earlier work finds 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. We test whether access to irrigation modulates the climate-migration poverty trap, since irrigation protects crops from heat. We regress measures of international and internal migration on decadal averages of temperature and rainfall, interacted with country-level data on irrigation and income. We find that irrigation access significantly weakens the climate-migration poverty trap, demonstrating the importance of considering alternative adaptation strategies when analyzing climate migration.

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# 1 Introduction

In 2017, the number of international migrants reached 258 million, or 3.4 % of the global population (United Nations, Department of Economic and Social Affairs, Population Division, 2017). At the same time, the worldwide stock of internal migrants is estimated to be around 763 million (United Nations, Department of Economic and Social Affairs, Population Division, 2013). Climate change, in the form of increased temperatures and increased frequency of extreme events, could further increase future numbers of migrants. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change accorded high agreement and medium evidence to the fact that climate change will increase displacement of people over the 21st century (IPCC, 2014). The World Bank estimates that between 31 and 143 million people could have to move internally by 2050 because of reduced crop productivity from lower water availability and because of sea-level rise and storm surges (Rigaud et al., 2018). In terms of refugee flows crossing international borders, 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 (Beine and Parsons, 2015; Coniglio and Pesce, 2015; 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; Beine and Parsons, 2017). A recent meta-analysis shows that the possibility of people being trapped following climate change is found in several studies using different methods (Beine and Jeusette, 2018). The World Bank's Groundswell Report also warns about the risk that vulnerable populations may remain trapped (Rigaud et al., 2018). However, the literature on climate change and international migration 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 the analysis of international migration and climate change.

In this paper, we seek to fill this gap, by integrating irrigation infrastructure into the analysis of climate change-induced migration. 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. In order to do so, we first verify the poverty trap found in the previous literature—that higher temperatures reduce emigration rates in low-income countries—and then control for irrigation as an important agricultural adaptation mechanism. Our results show that access to irrigation significantly weakens the 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 1960'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 1960. 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] 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), irrigation data 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 first demonstrate that higher temperatures decrease emigration rates in the low-income countries in our sample, according to a poverty trap as in Cattaneo and Peri (2016) and Beine and Parsons (2017). 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. The effect of irrigation is found to be significant both for emigration rates and for urbanization rates, which is important since rural-urban migration is considered the most likely migration response following climate change (Barrios

[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).

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

et al., 2006; Rigaud et al., 2018).[3]

We contribute to the literature on climate change adaptation and also the literature on environmental migration, which 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 weather anomalies on long-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 groundwater access reduces internal migration (Fishman et al., 2017; Zaveri et al., 2018).

Our paper makes three important contributions to the literature. It is 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 holds for both rural-urban migration and international migration, but that its relative effect is larger on international migration, which is more costly and hence subject to a stronger liquidity constraint. Third, as a more general contribution, our paper demonstrates and emphasizes the importance of considering multiple adaptation options in the context of climate change. Future research should aim to integrate a wider set of alternative adaptation options into the analysis of climate change and migration.

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

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

decision that incorporates wealth levels and access to irrigation. Section 4 describes the data sources 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.

## 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 across Africa (Kurukulasuriya et al., 2006) and Asia (Welch et al., 2010; Auffhammer et al., 2012; Taraz, 2018). Agronomic studies show that irrigation reduces heat stress on crops through a cooling effect on local temperatures and it also increases soil moisture (Bonfils and Lobell, 2007; Burke and Lobell, 2009; Siebert et al., 2014). Irrigation acts as a form of self-insurance, since irrigating farmers typically have higher mean yields and lower variance of profits (Foudi and Erdlenbruch, 2011; Troy et al., 2015). 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, in passing, that investment in irrigation might affect the climate–migration relationship, but they do not integrate it into their empirical analysis. Beine and Parsons (2015) analyze access to groundwater and find that shortfalls in precipitation increase migration 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 access to an alternative means of adaptation than migration. 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 higher rates 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. Also in India, in a cross-sectional analysis, Zaveri et al.

[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.

(2018) find that higher rates of irrigation in a district are associated with a lower probability of temporary migration. 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.

# 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 deciding whether to migrate. Irrigation reduces the negative impact of "bad weather" factors.[6] Such bad weather factors are likely multidimensional and include higher than optimal temperatures or low 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, we include both temperature and precipitation to avoid omitted variable bias due to the correlation between the two (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. In the first period, individuals (or "farmers") earn wages $w_0$:

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

with $\epsilon_0$ normally distributed with expectation zero and variance $\sigma_0^2$.

The expected wage $\mu_0$ is assumed to decrease in temperature $\frac{\partial \mu_0(T_0,I_0)}{\partial T_0} < 0$ but having

[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).

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 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 $\epsilon_1$ normally distributed with expectation zero and variance $\sigma_1^2$.

We assume 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 $\Phi$ 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 area equipped for irrigation in each country.

# 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

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

and summing all flows from a specific country.[8] 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 from the World Urbanization Prospects (UN, 2014). This data set, which spans 1950 to 2010, provides the proportion of each country's population living in urban areas. We 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, we exclude from the sample countries that are fossil fuel dependent. Specifically, we exclude countries whose share of fuel exports over GDP exceeds 40% in the year 2000 according to the World Development Indicators.[9] These countries have little cropland and are less dependent on agriculture, since they have resource rents that enable them to endure agricultural shocks.

## 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), national surveys, census reports, and statistical yearbooks.[10] The area equipped for irrigation represents irrigation infrastructure and differs from actual irrigated area, which should reduce contemporaneous endogeneity with weather factors. We are interested in the proportion of cropland equipped for irrigation (see Appendix Figure A1). To calculate this, we use gridded data on 1960's cropland areas from the History Database of the Global Environment, HYDE 3.2, produced by Klein Goldewijk and van Drecht (2006).

[8]This measure may create negative flows, 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.

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

[10]The data include full and partial control irrigation, equipped lowlands irrigation and areas equipped for spate irrigation, but exclude rainwater harvesting.

## 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 to the country level. In the first method, we aggregate gridded weather outcomes to the country level using backcasted 1970's gridded population weights from the Global Population Count Grid Time Series Estimates (GPCGTSE) (CIESIN, 2017).[11] These weights were developed in CIESIN (2011a) and adjusted to UN population data to give the best possible population estimate in those years. In the second method, we aggregate gridded weather using area weights from the Global Rural-Urban Mapping Project (GRUMP) (Balk et al., 2006) version1 (CIESIN, 2011b).

Although anomalies[12] are sometimes used in analyses of migration (Marchiori et al., 2012; Beine and Parsons, 2015), we use temperature and precipitation in 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 weather, we follow Missirian and Schlenker (2017) and use average weather during the maize growing season in each origin country. We do this because maize is a staple commodity grown in many countries around the world that 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 missing data on maize growing season dates, we instead use average monthly weather based on the entire twelve-month calendar year.[13]

[11] This is the earliest year for which the GPCGTSE data are available.

[12] Anomalies are deviations from the long term mean divided by the long term standard deviation.

[13] 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), but such measures require daily data on temperature and precipitation.

## 4.4 Other data

We use cereal yield data, measured in kilograms per hectare of harvested land, from the World Bank (2017).[14] GDP per capita data come from the Penn World Table (2009), and the data on the value added in agriculture (as % of GDP) 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. Appendix A provides a list of the countries in each group. 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 have a lower emigration rate (1.48%) then the middle-income countries (2.80%). The average urbanization rate in the poor countries in the sample is 19.7 % compared to 40.4 % in the middle-income countries. The average share of irrigated cropland in 1960 was 12.3% in the middle-income countries versus 3.33% 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.

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 for emigration and in 1950 for urbanization rates). 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.

[14]The cereal yield data includes the crops wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains.

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) |
| Urban population share | 0.351 | 0.404 | 0.197 |
| | (0.216) | (0.214) | (0.129) |
| Share of 1960 cropland irrigated | 0.100 | 0.123 | 0.0333 |
| | (0.173) | (0.191) | (0.0681) |
| Land under cereal production, million hectares | 3.974 | 4.751 | 1.697 |
| | (13.70) | (15.75) | (1.988) |
| Cereal production, million metric tons | 9.581 | 12.23 | 1.827 |
| | (42.00) | (48.36) | (2.312) |
| Cereal yield, metric tons per hectare | 1.862 | 2.103 | 1.153 |
| | (1.540) | (1.684) | (0.589) |
| Real GDP per capita, 2011 USD | 4892.8 | 6046.8 | 1523.5 |
| | (7615.3) | (8363.7) | (2823.8) |
| Temperature, C (population weights) | 23.48 | 23.25 | 24.16 |
| | (4.158) | (4.060) | (4.371) |
| Temperature, C (area weights) | 23.73 | 23.45 | 24.54 |
| | (4.273) | (4.231) | (4.301) |
| Precipitation, 100mm/month (population weights) | 1.385 | 1.417 | 1.294 |
| | (0.885) | (0.966) | (0.587) |
| Precipitation, 100mm/month (area weights) | 1.376 | 1.414 | 1.265 |
| | (0.923) | (0.996) | (0.660) |
| Number of countries | 105 | 78 | 27 |

*Note*: Mean coefficients. Standard deviations in parentheses. Sample consists of 105 poor and middle-income countries. The table presents averages of each variable for each decade that the variable is available. Temperature and precipitation values are calculated over the maize growing season in each country.

# 5 Empirical strategy

## 5.1 Yield regressions

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

$$\begin{aligned} ln(Yield_{it}) =& \beta_1 Temp_{it} + \beta_2 Temp_{it} \times Irrig_i + \beta_3 Prec_{it} + \beta_4 Prec_{it} \times Irrig_i + \\ & X_{it} + \alpha_i + \gamma_t + \epsilon_{it}, \end{aligned} \quad (5)$$

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 1960's crop land that was equipped for irrigation. We use the share of irrigated cropland at the start of the period of migration 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. 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 $\alpha_i$ is a country fixed effect that accounts for time-invariant factors that affect crop yields and $\gamma_t$ is a year fixed effect. Standard errors are clustered at country level. The regression spans 1961 to 2000, with some missing observations and the sample is poor and middle-income countries that are not high fuel-exporters.

Note that this linear specification of yields should be considered a first-order approximation to actual weather effects on yields, which clearly are non-linear (Schlenker and Roberts, 2009; Schlenker and Lobell, 2010). Since the weather data needed for the estimations should go back to the 1950s and 1960s, we cannot use daily data at a global level to capture non-linear effects. Our goal with the yield regression is only to show evidence of the protective effect of irrigation also on the actual data used in the subsequent migration analysis.

### 5.2 Migration regressions

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

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

where $Migr_{it}$ is either the emigration rate for the decade ending in year $t$ or the urbanization rate in year $t$. 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 decade prior to $t$. $Income_{ij}$ is a dummy that equals one if country $i$ is in the $j$th income quartile (based on 1990's GDP per capita).[15] We include country fixed effects ($\phi_i$) and a set of decade-by-region dummies ($\phi_{r,t}$) 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 potential differences, over time, in migration rates from poor countries versus middle-income countries. We cluster the regression at the country level. Following Cattaneo and Peri (2016) and Beine and Parsons (2017), 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

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

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 1960. As above, the regression includes country fixed effects, region-by-decade dummies, and

[15] Following other authors (Beine and Parsons, 2015; Cai et al., 2016; Cattaneo and Peri, 2016) we use the 1990 income distribution rather than the initial time period distribution, because there are a higher number of missing values for GDP for earlier years.

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

The results of our yield regressions are shown in Appendix Table A1. We focus on the interaction coefficients between temperature and irrigation, because these results are key for our subsequent migration analysis. Columns (1) and (3) use population-weighted weather and columns (2) and (4) use area-weighted weather. All columns include controls for GDP per capita interacted with weather, to ensure that the coefficient on irrigation truly captures the impact of irrigation, rather than the general level of development in the country. Columns (1) and (2) show the results controlling for 1960's GDP per capita interacted with the weather variables. Since using the initial year's GDP per capita level drops countries for whom the data were not available, in particular poor countries, we also show the results when controlling for interactions between the weather factors and GDP per capita in 1970 (columns (3) and (4)).[16] We see the negative impact of higher temperatures, but a positive interaction coefficient between temperature and irrigation showing that irrigation access offsets the negative impacts of higher temperatures on yields. The effect of irrigation on the negative impact of temperature is highly significant except for column (3) that uses population-weighted weather and controls for GDP per capita in 1970. Higher precipitation increases yields, and higher irrigation reduces the effect of precipitation.

In terms of magnitudes, if we compare a country with the mean level of irrigation in 1960 (across all countries) to a country that is one standard deviation above this mean, the

[16]The sample includes 74 countries when using GDP per capita in 1960, and 95 countries when using GDP per capita in 1970.

reduction in yields from a 1° C increase in temperature will be 33% 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 1960 (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 11.5% lower for the country with the higher level of irrigation.[17]

## 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 et al., 2014). For comparison with the literature, Table 2 replicates the results of Cattaneo and Peri (2016) on our sample, 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.[18] Precipitation does not have a significant effect on long-term rates of emigration, as in other analyses of international migration (Beine and Parsons, 2015; Cai et al., 2016; Cattaneo and Peri, 2016).

Higher temperatures are also associated with a lower rate of urbanization in poorer countries.[19] 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

[17]These calculations are done using the coefficients from Column (2).

[18]A 1° C increase in temperatures leads to a 63.8% reduction in emigration from countries in the bottom quartile (column (1)). The estimate is comparable to the literature (Cattaneo and Peri, 2016), but here we use the updated weather data from Willmott and Matsuura (2018) and temperatures in absolute levels and not in logs.

[19]For urbanization (columns (3) and (4)), the sample size is 7* 105 countries, compared to four decades of observations of emigration rates in columns (1) and (2).

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

| | (1) Emigration | (2) Emigration | (3) Urbanization | (4) Urbanization |
|---|---|---|---|---|
| Quartile=1 * Temperature | -1.017* | -1.357** | -0.0506** | -0.0593** |
| | (0.580) | (0.595) | (0.0246) | (0.0255) |
| Quartile=2 * Temperature | 0.885* | 0.642 | -0.0142 | -0.0176 |
| | (0.447) | (0.479) | (0.0246) | (0.0273) |
| Quartile=3 * Temperature | 0.368 | 0.106 | 0.00721 | 0.00374 |
| | (0.295) | (0.330) | (0.0179) | (0.0197) |
| Quartile=4 * Temperature | 0.331 | 0.109 | 0.00349 | 0.00532 |
| | (0.377) | (0.383) | (0.0332) | (0.0378) |
| Quartile=1 * Precipitation | -0.740 | -0.772 | -0.128*** | -0.154*** |
| | (0.760) | (0.850) | (0.0437) | (0.0438) |
| Quartile=2 * Precipitation | 0.0476 | 0.191 | 0.0536* | 0.0598** |
| | (0.672) | (0.721) | (0.0282) | (0.0301) |
| Quartile=3 * Precipitation | -0.0854 | -0.523 | -0.0617* | -0.0790** |
| | (0.355) | (0.399) | (0.0346) | (0.0375) |
| Quartile=4 * Precipitation | 0.181 | 0.954 | -0.0326 | -0.0141 |
| | (1.001) | (1.580) | (0.0779) | (0.0765) |
| Observations | 420 | 420 | 735 | 735 |
| $R^2$ | 0.216 | 0.213 | 0.814 | 0.816 |
| Adjusted $R^2$ | 0.164 | 0.161 | 0.802 | 0.804 |

*Note*: Standard errors in parentheses. Sample is 105 poor and middle-income countries. Years 1960-2000 for migration data and 1950-2010 for urbanization data. 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 with GPCGTSE population weights (Columns 1 & 3) or with GRUMP area weights (Columns 2 & 4). 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.

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

with higher precipitation levels, contrary to ex ante hypotheses on urbanization (Henderson et al., 2017). This may come from the level of aggregation; Hossain and Ahsan (2018) show the importance of spatial spillovers when studying phenomena at a subnational level such as rural-urban migration.

Table 3 presents the main results of the effect of irrigation on emigration. As expected, 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 in columns (2) and (5). 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 1960'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 67% reduction in emigration from poor countries with the mean level of irrigation in 1960. For poor countries that are one standard deviation above the mean irrigation in 1960, we only see a 36% reduction in emigration.[20] Thus, this amount of increase of irrigation leads to a 46.2% reduction in the impact of temperature on outmigration.

The effects of irrigation access are also tested for urbanization, which we use as a proxy

[20]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 1960's irrigation.

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

| | Population weights | | | Area weights | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Temperature | 0.257 | 0.480* | 0.455* | 0.0121 | 0.228 | 0.211 |
| | (0.236) | (0.249) | (0.248) | (0.259) | (0.274) | (0.277) |
| Poor=1 * Temperature | | -1.507** | -1.885*** | | -1.589** | -1.778*** |
| | | (0.606) | (0.605) | | (0.638) | (0.677) |
| Poor=1 * Temperature * 1960 irrig | | | 9.581*** | | | 5.966 |
| | | | (3.375) | | | (3.783) |
| Precipitation | -0.146 | -0.0250 | -0.0213 | -0.204 | -0.0856 | -0.0868 |
| | (0.352) | (0.377) | (0.377) | (0.398) | (0.443) | (0.443) |
| Poor=1 *Precipitation | | -0.729 | -1.265 | | -0.683 | -1.109 |
| | | (0.835) | (0.945) | | (0.949) | (1.104) |
| Poor=1 * Precipitation * 1960 irrig | | | 12.76 | | | 10.82 |
| | | | (25.13) | | | (28.29) |
| Observations | 420 | 420 | 420 | 420 | 420 | 420 |
| $R^2$ | 0.194 | 0.212 | 0.221 | 0.189 | 0.206 | 0.210 |
| Adjusted $R^2$ | 0.153 | 0.168 | 0.174 | 0.149 | 0.162 | 0.162 |

*Note*: Standard errors in parentheses. Sample is 105 poor and middle-income countries. Years 1960-2000. 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 with GPCGTSE population weights (Columns 1–3) or GRUMP area weights (Columns 4–6). 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. 1960 irrig measures the share of 1960's crop land irrigated.
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$

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

| | Population weights | | | Area weights | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Temperature | -0.00481 | 0.00513 | 0.00572 | -0.0107 | 0.00137 | 0.00167 |
| | (0.0119) | (0.0137) | (0.0138) | (0.0151) | (0.0174) | (0.0174) |
| Poor=1 * Temperature | | -0.0554** | -0.0834*** | | -0.0605** | -0.0884*** |
| | | (0.0278) | (0.0286) | | (0.0303) | (0.0319) |
| Poor=1 * Temperature * 1960 irrig | | | 0.344** | | | 0.311* |
| | | | (0.151) | | | (0.160) |
| Precipitation | -0.0248 | 0.00400 | 0.00589 | -0.0293 | 0.00535 | 0.00738 |
| | (0.0274) | (0.0278) | (0.0281) | (0.0296) | (0.0292) | (0.0296) |
| Poor=1 * Precipitation | | -0.132** | -0.165*** | | -0.160*** | -0.200*** |
| | | (0.0518) | (0.0581) | | (0.0522) | (0.0584) |
| Poor=1 * Precipitation * 1960 irrig | | | 0.827 | | | 1.004 |
| | | | (0.845) | | | (1.047) |
| Observations | 735 | 735 | 735 | 735 | 735 | 735 |
| $R^2$ | 0.808 | 0.811 | 0.812 | 0.808 | 0.812 | 0.813 |
| Adjusted $R^2$ | 0.797 | 0.800 | 0.801 | 0.798 | 0.801 | 0.802 |

*Note*: Standard errors in parentheses. Sample is 105 poor and middle-income countries. Years 1950-2010. The dependent variable is the urban population share. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL with GPCGTSE population weights (Columns 1–3) or GRUMP area weights (Columns 4–6). 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. The variable 1960 irrig measures the share of 1960's crop land irrigated.

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

for rural-urban migration. Table 4 shows that poor countries with irrigation display a much smaller negative response to higher temperatures, as can be seen in columns (3) and (6). For poor countries that had the mean level of irrigation in 1960, a 1°C increase in decadal average temperatures leads to a 6.4 percentage points reduction in urbanization. For poor countries which were one standard deviation above the mean level of irrigation in 1960, we only see a 4.1 percentage points reduction in urbanization. Thus, this amount of increase of area equipped for irrigation reduces the impact of temperature on outmigration by 34.4%.

### 6.3 Migration regressions, robustness checks

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

First, we consider how irrigation influences migration for countries that rely heavily on agriculture. We define agricultural countries to be those countries in the top quartile of agricultural value added as a share of GDP.[21] 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 may just not be in the top quartile in terms of their dependence).

The results in Table 5 show that higher temperatures have a negative effect on emigration from agricultural countries (columns (1) and (4)) and that access to irrigation cushions this effect (columns (2) and (5)). When we include both sets of triple interaction (agriculture*temperature*irrigation and poor*temperature*irrigation) in columns (3) and (6) the triple interactions are not individually significant, which is perhaps unsurprising since the poor variable and the agricultural country variable are quite collinear. However, an F test of the joint significance of both triple interaction terms demonstrates that they are jointly

[21] The sample size is reduced by 6 countries, for which data on agricultural value added were missing.

significant at the 5% level. The results for urbanization are similar (Table 6). Higher temperatures reduce urbanization in agricultural countries, and access to irrigation softens this effect. Taken together, Tables 5 and 6 strengthen our evidence for the protective role of irrigation, because they demonstrate that we find a protective effect of irrigation, whether we focus on poor countries or on agricultural countries.

Next, we show that our results are robust to an alternative specification, namely measuring irrigation as a dummy variable. In our main specification, we measure irrigation as the proportion of 1960's cropland equipped for irrigation. In this robustness test, we instead define irrigation as a dummy, whereby a country is considered to be "high irrigation" if it was above some threshold for irrigation (across the set of poor and middle income countries) in 1960. Table A2 presents the results of this robustness check for emigration (columns (1) to (3)) and for urbanization (columns (4) to (6)). We vary the threshold for high irrigation to be the median of 1960's irrigated cropland, the 40th percentile, or the 60th percentile. For urbanization we find that higher temperatures reduce urbanization in poor countries, and higher levels of irrigation attenuates this effect significantly, at all threshold levels in columns (4) to (6). For emigration, the effect is significant for shares of irrigation above the 60th percentile (column (3)). For the 40th and 50th percentile of 1960's irrigation share, the triple interaction coefficient still has the expected positive effect, but it is not significant.

# 7 Discussion

Despite our robustness checks, we note some key caveats regarding our analysis.

First, 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, higher temperatures affect many outcomes, including conflict (Hsiang et al., 2013; Burke et al., 2015), mortality (Deschênes and Greenstone, 2011), health (Deschênes, 2014), labor productivity (Zivin and Neidell, 2014;

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

| | Population weights | | | Area weights | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Temperature | 0.357 | 0.353 | 0.440* | 0.0962 | 0.0941 | 0.191 |
| | (0.239) | (0.239) | (0.249) | (0.272) | (0.272) | (0.287) |
| Agri=1 * Temperature | -1.163** | -1.562*** | -1.187** | -1.226** | -1.574*** | -1.327** |
| | (0.517) | (0.557) | (0.581) | (0.524) | (0.549) | (0.555) |
| Agri=1 * Temperature * 1960 irrig | | 17.23*** | 11.18 | | 16.49** | 10.30 |
| | | (6.508) | (7.859) | | (6.352) | (6.641) |
| Poor=1 * Temperature | | | -1.202** | | | -1.165* |
| | | | (0.590) | | | (0.606) |
| Poor=1 * Temperature * 1960 irrig | | | 5.116 | | | 4.070 |
| | | | (6.684) | | | (5.508) |
| Precipitation | 0.329 | 0.332 | 0.268 | 0.292 | 0.292 | 0.222 |
| | (0.363) | (0.364) | (0.393) | (0.423) | (0.424) | (0.464) |
| Agri=1 * Precipitation | -1.926** | -2.386*** | -1.730*** | -1.994** | -2.457*** | -1.780*** |
| | (0.770) | (0.732) | (0.576) | (0.876) | (0.815) | (0.657) |
| Agri=1 * Precipitation * 1960 irrig | | 28.19 | -39.44 | | 28.01 | -84.59* |
| | | (23.64) | (34.54) | | (25.61) | (43.46) |
| Poor=1 * Precipitation | | | -1.240 | | | -1.361 |
| | | | (0.817) | | | (0.882) |
| Poor=1 * Precipitation * 1960 irrig | | | 82.71** | | | 127.4*** |
| | | | (32.18) | | | (42.56) |
| Observations | 396 | 396 | 396 | 396 | 396 | 396 |
| $R^2$ | 0.222 | 0.229 | 0.247 | 0.219 | 0.225 | 0.246 |
| Adjusted $R^2$ | 0.176 | 0.179 | 0.190 | 0.173 | 0.175 | 0.188 |
| p value for the F test of joint significance of both temperature triple interaction terms: | | | 0.0308 | | | 0.0369 |

*Note*: Standard errors in parentheses, clustered at country level. Sample is 105 poor and middle-income countries. Years 1960-2000. 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 with GPCGTSE population weights (Columns 1–3) or GRUMP area weights (Columns 4–6). 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. The variable 1960 irrig measures the share of 1960's crop land irrigated. In Column (3) and (6) the p-value at the bottom of the table test for the joint significance of the two temperature triple interaction terms (poor*temp*irrig and agri*temp*irrig).
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$

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

| | Population weights | | | Area weights | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Temperature | -0.00166 | -0.00402 | -0.000207 | -0.00615 | -0.00912 | -0.00313 |
| | (0.0140) | (0.0139) | (0.0140) | (0.0181) | (0.0181) | (0.0184) |
| Agri=1 * Temperature | -0.0341 | -0.0716** | -0.0633 | -0.0456 | -0.0810*** | -0.0689* |
| | (0.0326) | (0.0300) | (0.0389) | (0.0338) | (0.0302) | (0.0348) |
| Agri=1 * Temperature * 1960 irrig | | 0.716** | 1.233*** | | 0.798** | 1.349*** |
| | | (0.350) | (0.457) | | (0.325) | (0.452) |
| Poor=1 * Temperature | | | -0.0502 | | | -0.0688* |
| | | | (0.0458) | | | (0.0405) |
| Poor=1 * Temperature * 1960 irrig | | | -0.312 | | | -0.326 |
| | | | (0.427) | | | (0.423) |
| Precipitation | -0.0373 | -0.0366 | -0.0191 | -0.0379 | -0.0369 | -0.0155 |
| | (0.0288) | (0.0290) | (0.0297) | (0.0308) | (0.0312) | (0.0314) |
| Agri=1 * Precipitation | 0.0488 | 0.0569 | 0.0758 | 0.0425 | 0.0489 | 0.0704 |
| | (0.0429) | (0.0533) | (0.0475) | (0.0473) | (0.0565) | (0.0477) |
| Agri=1 * Precipitation * 1960 irrig | | -1.733 | -3.028** | | -1.675 | -3.639** |
| | | (1.255) | (1.351) | | (1.235) | (1.672) |
| Poor=1 * Precipitation | | | -0.153*** | | | -0.186*** |
| | | | (0.0533) | | | (0.0537) |
| Poor=1 * Precipitation * 1960 irrig | | | 3.290** | | | 4.107** |
| | | | (1.329) | | | (1.731) |
| Observations | 693 | 693 | 693 | 693 | 693 | 693 |
| $R^2$ | 0.808 | 0.812 | 0.816 | 0.809 | 0.813 | 0.818 |
| Adjusted $R^2$ | 0.796 | 0.800 | 0.803 | 0.797 | 0.801 | 0.805 |

*Note*: Standard errors in parentheses. Sample is 105 poor and middle-income countries. Years 1950-2010. The dependent variable is the urban population share. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL with GPCGTSE population weights (Columns 1–3) or GRUMP area weights (Columns 4–6). 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. The variable 1960 irrig measures the share of 1960's crop land irrigated.

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

Somanathan et al., 2015) and industrial total factor productivity (Zhang et al., 2018). Each of these outcomes may, in turn, affect migration (see, for example, Deschênes and Moretti (2009)). Thus our regressions do not capture only the agricultural channel, but, in fact, capture the total effect of temperature on migration, which may include non-agricultural mechanisms. However, we do not attempt to control for these other channels, due to the "bad control" problem described in Angrist and Pischke (2008). Furthermore, our focus is the modulating role of irrigation. Irrigation affects agricultural incomes directly and, moreover, either does not affect the other factors listed above, or, only affects them via agricultural income. Thus, we feel confident that the agricultural channel drives our irrigation results.

Second, we use irrigation from 1960's to reduce the endogeneity of irrigation relative to migration and temperature in our regression. However, it is possible that 1960's irrigation levels may be correlated with other unobserved factors that influence the temperature–migration relationship in agriculture. While we are unable to disentangle this issue using cross-country data, future work on migration at the sub-national level could potentially address this issue, by employing instruments for irrigation levels.

Third, while the analysis of international migration necessarily involves the use of cross-country data sets, an associated limitation 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, global patterns we have uncovered here also hold 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).

Fourth, country-level studies would also allow for deeper analysis of internal migration.

Our current analysis uses urbanization rates to proxy for rural-urban migration, due to limited data on internal migration flows for an international panel of countries. Hence we do not capture the effects of irrigation on rural-rural migration. In addition, the use of micro data would permit a finer grain analysis of the differences between international and rural-urban migration, the role of irrigation in influencing these migrations, as well as potentially exploring heterogeneity in the migration response across different types of individuals. Such work could better address all the institutional factors affecting farmers' choices at the household and the community level as well as explore nuanced issues around the formation of poverty traps (Barrett et al., 2018).

Another limitation of our study is that we model irrigation as a fixed, exogenous 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, although in the short run irrigation can shield yields from weather shocks, in the long run access to irrigation can induce farmers to plant more water-intensive crops, thus increasing the weather sensitivity of agriculture, an effect which has been termed maladaptation (Hornbeck and Keskin, 2014; Damania et al., 2017). An analysis of this effect was out of scope of the current analysis—due to lack of international panel data on planted crop area—but this is a fruitful topic for future research 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, and Fishman (2018) underlines the very real limits of available water for a long term adaptation strategy relying on irrigation. The social losses due to water overuse, in particular over extraction of groundwater, have been estimated to be substantial (Sayre and Taraz, 2019). It is thus not evident whether reliance on irrigation should be part of an integral strategy of adaptive development (Agrawal and Lemos, 2015) that aims at integrating adaptation within sustainable development. 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

Understanding the drivers behind international and internal migration is of paramount importance, particularly in light of accelerating climate change. 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. We focus on irrigation access as one of the major means of adaptation in agriculture, since the recent literature has emphasized an agricultural channel as driving climate change induced migration. Using a global data set of low- and middle-income countries, we have demonstrated 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 key specification variations: to focusing on agricultural countries, instead of poor countries; and to measuring irrigation as a dummy variable, rather than in levels.

The relation between climate and migration is complex and the mechanisms of the influence of climatic factors on migration need to be taken into account. Migration as an adaptation strategy is limited to the extent that poor parts of the population may remain trapped because of the cost of relocation (Black et al., 2011). On the other hand, farm households, in particular, adapt to climate change and have a wide variety of means to do so, such as shifting planting dates, planting drought-resistant crops, intensifying agricultural means of production and investing in irrigation (Burke and Lobell, 2009; Auffhammer and Schlenker, 2014; McCord et al., 2018). Here, we accounted for one of the major means of adaptation in the agricultural sector, which could attenuate the link between agricultural productivity and migration flows. Future research should consider a broad range of adaptation strategies affecting other mechanisms behind climate-induced migration and how these could influence the extent to which migration would be affected by climate change.

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# 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, Cameroon, Cape Verde, 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, Saint Vincent and the Grenadines, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Sierra Leone, Solomon Islands, South Africa, Sri Lanka, Suriname, Swaziland, Syrian Arab Republic, Thailand, Trinidad and Tobago, Tunisia, Uruguay, Vanuatu, Venezuela, Vietnam, and Zimbabwe.

# B Appendix Figures and Tables

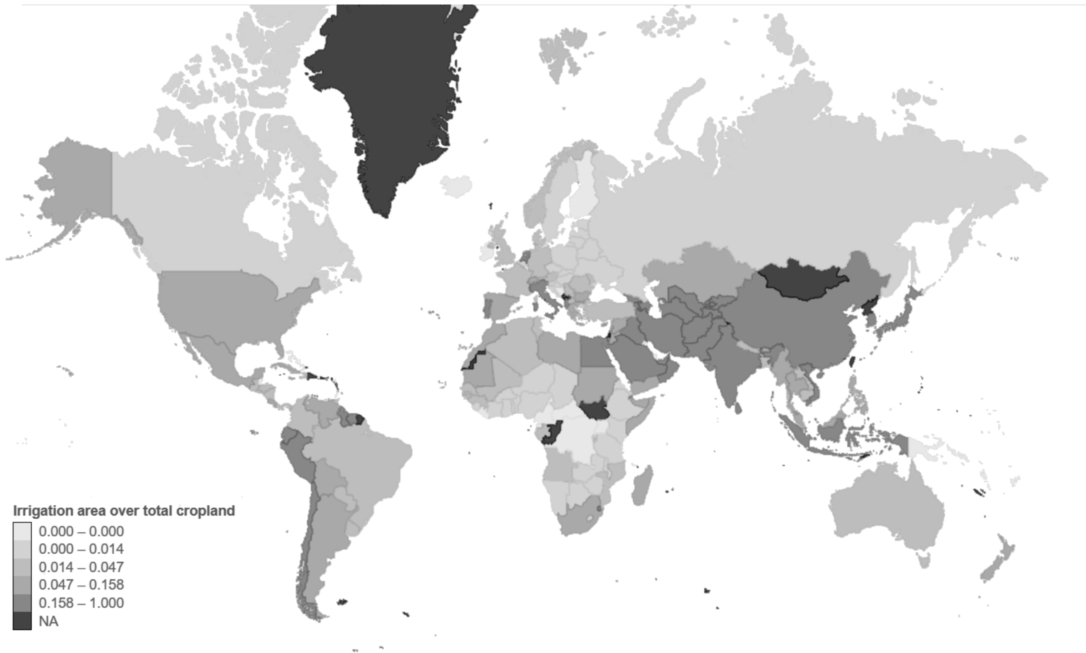


Figure A1: Map of area equipped for irrigation in 1960

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

Table A1: Temperature, irrigation, and crop yields.

| | Pop. weights | Area weights | Pop. weights | Area weights |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Temperature | -0.125*** | -0.139*** | -0.0866*** | -0.0914*** |
| | (0.0334) | (0.0367) | (0.0245) | (0.0249) |
| 1960 irrig * Temperature | 0.200*** | 0.232*** | 0.122* | 0.163** |
| | (0.0517) | (0.0559) | (0.0639) | (0.0627) |
| Precipitation | 0.124*** | 0.121*** | 0.121*** | 0.128*** |
| | (0.0375) | (0.0396) | (0.0291) | (0.0301) |
| 1960 irrig * Precipitation | -0.507* | -0.632** | -0.427** | -0.492** |
| | (0.300) | (0.298) | (0.199) | (0.222) |
| Observations | 2920 | 2920 | 3740 | 3740 |
| $R^2$ | 0.371 | 0.372 | 0.310 | 0.310 |
| Adjusted $R^2$ | 0.362 | 0.362 | 0.301 | 0.302 |

*Note*: Standard errors in parentheses. Sample is 105 poor and middle-income countries. Years 1961-2000. The dependent variable is yield in tons of cereal harvested per hectare planted. Country fixed effects and year fixed effects. Standard errors clustered at country level. Average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL with GPCGTSE population weights (Columns 1–2) or GRUMP area weights (Columns 3–4). The variable 1960 irrig measures the share of 1960's crop land irrigated. Columns (1) and (2) control for 1960's GDP per capita interacted with temperature and precipitation terms. Columns (3) and (4) control for 1970's GDP per capita interacted with temperature and precipitation terms.

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

Table A2: Temperature, irrigation, and emigration or urbanization, with different thresholds for high irrigation.

| | (1) Emigration 50th pctl irrig | (2) Emigration 40th pctl irrig | (3) Emigration 60th pctl irrig | (4) Urbanization 50th pctl irrig | (5) Urbanization 40th pctl irrig | (6) Urbanization 60th pctl irrig |
|---|---|---|---|---|---|---|
| Temperature | 0.468* | 0.478* | 0.465* | 0.00541 | 0.00579 | 0.00542 |
| | (0.248) | (0.248) | (0.248) | (0.0137) | (0.0137) | (0.0137) |
| Poor=1 * Temperature | -1.732*** | -1.741*** | -1.817*** | -0.0947*** | -0.0948*** | -0.0925*** |
| | (0.614) | (0.620) | (0.602) | (0.0267) | (0.0274) | (0.0268) |
| Poor=1 * High irrigation=1 * Temperature | 1.039 | 0.844 | 1.512** | 0.0830*** | 0.0816*** | 0.0799*** |
| | (0.712) | (0.732) | (0.713) | (0.0224) | (0.0234) | (0.0228) |
| Precipitation | -0.0265 | -0.0211 | -0.0252 | 0.00499 | 0.00531 | 0.00505 |
| | (0.377) | (0.378) | (0.377) | (0.0280) | (0.0279) | (0.0280) |
| Poor=1 * Precipitation | -1.487* | -1.254 | -1.442* | -0.176*** | -0.203*** | -0.169*** |
| | (0.882) | (1.008) | (0.862) | (0.0544) | (0.0499) | (0.0545) |
| Poor=1 * High irrigation=1 * Precipitation | 2.734*** | 1.252 | 2.566*** | 0.124*** | 0.191*** | 0.102** |
| | (0.785) | (1.271) | (0.738) | (0.0444) | (0.0556) | (0.0443) |
| Observations | 420 | 420 | 420 | 735 | 735 | 735 |
| $R^2$ | 0.219 | 0.215 | 0.221 | 0.813 | 0.814 | 0.813 |
| Adjusted $R^2$ | 0.171 | 0.167 | 0.173 | 0.802 | 0.803 | 0.802 |

*Note*: Standard errors in parentheses. Sample is 105 poor and middle-income countries. Years 1960-2000. Decadal average temperature (C) and precipitation (100 mm/month) during maize growing season are from UDEL with GPCGTSE population weights. 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 1960, depending on the column of the table.

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