Climate Shocks and the Timing of Migration from Mexico

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Abstract

Although evidence is increasing that climate shocks influence human migration, it is unclear exactly when people migrate after a climate shock. A climate shock might be followed by an immediate migration response. Alternatively, migration, as an adaptive strategy of last resort, might be delayed and employed only after available *in-situ* (in-place) adaptive strategies are exhausted. In this paper, we explore the temporally lagged association between a climate shock and future migration. Using multilevel event-history models, we analyze the risk of Mexico-U.S. migration over a seven-year period after a climate shock. Consistent with a delayed response pattern, we find that the risk of migration is low immediately after a climate shock and increases as households pursue and cycle through *in-situ* adaptive strategies available to them. However, about three years after the climate shock, the risk of migration decreases, suggesting that households are eventually successful in adapting *in-situ*.

Keywords

Climate; Adaptation; Migration; Response pattern; Timing; Rural Mexico

Introduction

Evidence is increasing that human migration patterns are impacted by climate change and associated climate shocks, raising many important and timely questions about the nature and nuances of this association (Bardsley and Hugo 2010; Black et al. 2011a; Bohra-Mishra et al. 2014; Gray and Bilsborrow 2013; Hunter et al. 2015; McLeman 2014). Among these questions, presently, it is unclear exactly when actors (persons, households, etc.) decide to migrate after a climate shock, if at all. In some cases, a climate shock may lead to an immediate migration response (Gray and Mueller 2012b). In other cases, migration, as an ex-situ adaptive strategy, is delayed, and is employed only after available *in-situ* (in-place) adaptive strategies are pursued and exhausted (Bardsley and Hugo 2010; Gray and Mueller 2012a).

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While a temporally lagged association between a climate shock and migration is intuitive when one considers that migration is often an adaptive strategy of last resort (Findlay 2011; Fischer and Malmberg 2001; McLeman 2011), existing research has yet to examine and compare competing forms of this association. Anchored theoretically in the New Economics of Migration and drawing from previous empirical research, we test three models of the temporally lagged association between a climate shock and migration. The first model posits an immediate migration response after a climate shock. The latter two models posit a delayed migration response. In the second model, the risk of migration is low immediately after a climate shock and increases thereafter. The third model is distinguished from the second in that, after a temporary increase in the risk of migration, the risk of migration decreases given an eventual successful transition to *in-situ* adaptation. These models are tested using two climate measures tapping deviations from long-term historical averages in temperature and precipitation extremes and detailed histories of Mexico-U.S. migration from the Mexican Migration Project (MMP).

Background

Following previous research on migration and population displacement caused by environmental conditions and climate change (Gray and Mueller 2012a; Nawrotzki et al. 2013; Williams 2015), our efforts to examine the temporally lagged association between a climate shock and migration have theoretical roots in the New Economics of Migration (NEM) (Stark and Bloom 1985). NEM is premised on the idea that households are decision-making units seeking to mitigate threats to their economic livelihoods. Especially in rural areas in developing countries, which is the focus of this paper, households often lack the resources necessary to self-insure against livelihood uncertainties, including those associated with climate threats (e.g., crop failures). Limited or no access to capital and credit markets, as well as the quality of these institutions if they do exist, prevent households from adapting *in-situ* to climate threats by, for example, employing technological means such as irrigation systems or improved farming techniques (Massey et al. 1998; Stark and Bloom 1985). Migration is therefore employed as an *ex-situ* adaptive strategy on the part of households who, rather than migrate as a unit, elect to send one or more members to locations where climatic and market conditions are uncorrelated with those at home (Massey et al. 1993). Through the vehicle of remittances, migrants provide a source of supplemental income that is used to stabilize livelihoods and facilitate production back home, with well-documented multiplier effects (Durand et al. 1996; Taylor 1999).

NEM provides a valuable point of entry for examining the temporally lagged association between a climate shock and migration. Under the assumption that a climate shock threatens households' livelihoods for a protracted period through adverse impacts on the agricultural sector (Boyd and Ibarraran 2009; Mueller et al. 2014; Nawrotzki et al. 2015a), NEM suggests at least three possibilities (hereafter, models) depicting the lagged association between a climate shock and migration (Fig 1). In contrast to the latter two models, the first model posits an immediate migration response after a climate shock. The latter two models suggest a delayed migration response, with the third model distinguished from the second by an eventual successful transition to *in-situ* adaptation.

In the first model (Fig 1, Panel A), the risk of migration is high immediately following a climate shock and declines thereafter. This can be explained with respect to one or more of the following dynamics: First, the climate shock may be extreme in its effects (e.g., a rapid-onset natural disaster) and force people to immediately migrate elsewhere (Gray and Mueller 2012b). However, it is worth noting that such moves likely involve the displacement of entire households (McLeman 2011), which is a slightly different migration dynamic than suggested by NEM. Second, an immediate migration response would follow if *in-situ* adaptive strategies are not readily available or accessible to households. Third, even if other *in-situ* strategies are available, unique cultural contexts may lead households to favor migration over other livelihood strategies (Kandel and Massey 2002; Massey and Espinosa 1997). For example, strong transnational migration networks may reduce the costs of migration so that even small environmental triggers lead to large migration responses (Bardsley and Hugo 2010).[1] Finally, environmental risk perceptions may play a role if migration is perceived as a viable and preferable adaptation strategy (Bylander 2013). Ultimately, the initially high risk of migration is likely to abate over time as the climate shock fades from view, as well as the fact that households most likely to migrate will have done so, leaving a pool of households less likely to move (Massey et al. 1994).

In contrast to an immediate response pattern, a delayed migration response pattern is also consistent with the insights of NEM. In settings where *in-situ* adaptive strategies are available and accessible to households (second model, Fig 1, Panel B), the risk of migration is likely to be low immediately following a climate shock and to gradually increase thereafter. In addition to accessing formal capital and credit markets, *in-situ* adaptive strategies include a plethora of options such as informal forms of borrowing, reducing nonessential expenditures, liquidating assets, drawing on family and social networks, and utilizing public assistance programs (Bardsley and Hugo 2010; Gray and Mueller 2012a; Osbahr et al. 2008). Given these options, households will first attempt to adapt in place (Findlay 2011; Fischer and Malmberg 2001). However, over time, *in-situ* adaptation resources may be drained, forcing households to explore alternative strategies such as migration (Dow et al. 2013; McLeman 2011). Households may likewise fail to successfully implement one or more *in-situ* adaptive strategies (Adger et al. 2009). For example, farmers seeking to switch to drought-resistant crops must navigate, perhaps for the first time, new and complex landscapes that include learning about the nutrient requirements of new crop varieties, securing necessary capital, and managing the project to completion (cf., Marra et al. 2003), with no guarantee that agricultural diversification will lessen livelihood uncertainties. With only limited success, households cycle through the set of *in-situ* adaptive strategies available to them, progressively exhausting these. All the while, the risk of migration increases.

However, through processes of trial and error, households might eventually successfully adapt in place (cf., Marra et al. 2003). In this model (third model, Fig 1, Panel C), the risk of

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[1]The socioeconomic context will also shape the directionality of the migration response (Black et al. 2011a). In a Latin American context, adverse climatic conditions often lead to an increase in international out-migration (Feng and Oppenheimer 2012; Gray and Bilsborrow 2013; Hunter et al. 2013). A decline in international migration has been observed in a few case studies of the African continent (Gray and Mueller 2012a; Henry et al. 2004). Under conditions of extreme poverty, households may become "trapped" in place when adverse environmental conditions undermine the resource base to finance a move (Black et al. 2011b).

migration is low immediately following a climate shock as households begin to pursue the set of *in-situ* adaptive strategies available to them. The risk of migration initially increases during a trial and error phase, which might be characterized by cycling through short-term coping strategies that do not offer permanent solutions to livelihood uncertainties (Berkes and Jolly 2002; IPCC 2012), but ultimately decreases as households succeed in adapting *in-situ*. For example, attempts to diversify agricultural production might flounder at first, but are corrected and improved over time, and are perhaps accompanied by new and complimentary efforts (e.g., agricultural intensification) that proceed with greater efficiency given accumulated knowledge and experience (Osbahr et al. 2008). As result, the necessity to diversify livelihoods through migration declines with the successful implementation of *in-situ* adaptation strategies.

The three models above entail different predictions about the nature of the lagged association between a climate shock and migration. In the current paper, we therefore test the following hypotheses:

> H1. The risk of migration is high immediately after a climate shock and decreases thereafter. This finding would indicate an immediate response pattern.

> H2. The risk of migration is low immediately after a climate shock and increases thereafter. This finding would indicate a delayed response pattern.

> H3. The risk of migration is low immediately after a climate shock, temporarily increases, and then decreases thereafter. This finding would indicate a delayed response pattern with an eventual successful transition to *in-situ* adaptation.

These hypotheses are tested while controlling for a range of household and community level factors, and can be contrasted against the null hypothesis (H0) that the magnitude of the association between a climate shock and migration is constant over time.

Approach

Data and Case

To empirically test our hypotheses, we combined detailed migration histories and sociodemographic data from the Mexican Migration Project (MMP)[2] with daily temperature and precipitation information from the Global Historical Climate Network–Daily (GHCN-D), released by the National Oceanic and Atmospheric Administration (NOAA). Since 1982, the MMP has collected data from four to six communities each year (Massey 1987). A random sample of 200 households is drawn from each community, and a detailed questionnaire is administered. Although not strictly representative of Mexico at large, validation exercises have demonstrated that the MMP accurately reflects the migration behavior and demographic characteristics of the international migrant population (Massey and Capoferro 2004; Massey and Zenteno 2000). Due to its detailed event histories and high data quality, the MMP has been employed in a wide range of migration studies (Fussell and Massey 2004; Hunter et al. 2013; Massey et al. 2015; Riosmena 2009).

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[2]The Mexican Migration Project (MMP) is a collaborative research project based at Princeton University and the University of Guadalajara. The MMP data are available at http://mmp.opr.princeton.edu.

Mexico constitutes a unique case, with a long history of international migration to the U.S. The origins of these movements can be traced to the early 1900s when Mexicans were recruited to work on railroad construction projects and as farm laborers across the U.S. South and Midwest (Durand and Arias 2000). Migration increased between 1942 and 1964 with the Bracero Program, a bi-national labor agreement designed to meet labor shortages on U.S. farms caused by U.S. participation in World War II (Calavita 1992). Migration continued after the Bracero Program was terminated (Massey et al. 2002), resulting, unexpectedly from a policy vantage point, in undocumented migration. The 1986 Immigration Reform and Control Act (IRCA) increased the border control budget and made employment of undocumented migrants illegal (Orrenius and Zavodny 2003). Despite increases in border enforcement efforts, undocumented migration to the U.S. continued to increase (Massey and Capoferro 2004; Massey and Riosmena 2010). For the most part, migrants originate from rural areas in Mexico, although, in recent decades, migration from urban areas has increased (Fussell and Massey 2004). Due to the focus on these rural sending regions, the MMP is an excellent data source for investigating livelihood-based migration dynamics. In line with the tenets of NEM, research has consistently demonstrated that the decision to migrate is a household-level decision, rather than a strategy for economic gain by isolated individual actors (Cohen 2004; Massey and Espinosa 1997).

Although most rural Mexican households do not rely entirely on agriculture, income from farming activities contributes in important ways to sustenance and livelihood portfolios (Conde et al. 2006; Wiggins et al. 2002; Winters et al. 2002). Agriculture contributes to between one- and two-thirds of household income (de Janvry and Sadoulet 2001). This reliance on agriculture makes rural Mexicans vulnerable to climatic shifts and resulting adverse impacts on crop production (Endfield 2007; Saldana-Zorrilla and Sandberg 2009; Schroth et al. 2009). Climate related vulnerability of the agricultural sector is amplified by a lack of technological infrastructure to guard against adverse climatic effects. For example, in 2001, only 23% of Mexico's cropland was irrigated (Carr et al. 2009).

Climate projections suggest that, over the 21st century, precipitation will decline across Mexico (Christensen et al. 2013) and temperatures will increase (Collins et al. 2013). Such trends will likely lead to an increase in the frequency and severity of climate extremes such as droughts (Wehner et al. 2011), with detrimental effects for the agricultural sector and dependent livelihoods. During the study period (1986-99), Mexico experienced an above-normal increase in temperature and associated drought conditions (Stahle et al. 2009) that resemble long-term climatic trends, providing suitable conditions to study the timing of climate-related migration.

Measures and Statistical Models

We take the household as our unit of analysis since decisions to migrate are frequently reached within the larger household unit (Cohen 2004; Stark and Bloom 1985). In contrast, our climate change measures were constructed for municipalities as the spatial unit of analysis. In this study, we focus on rural MMP communities located in 68 municipalities dispersed across Mexico, based on the assumption that climate impacts on livelihoods and migration dynamics are stronger in rural than urban areas (Nawrotzki et al. 2015a). Rural

communities are defined as located in towns (2,500 – 10,000 inhabitants) or *ranchos* (< 2,500 inhabitants). Fig 2 displays the geographic location of the study municipalities, as well as the location of weather stations for which climate information was available.

At the time of this study, the GHCN-D was the only data source that provided daily temperature and precipitation information for the 38-year period (1961-1999) required to construct of our climate shock measures. Rigorous quality checks are periodically applied to the GHCN-D to guarantee a high degree of accuracy (Menne et al. 2012). Multiple studies have employed the GHCN-D to explore long-term patterns of climate change and variability for various world regions (e.g., Alexander et al. 2006; Caesar et al. 2006).

In this study, we investigate climate-migration associations for the period of 1986-99. We were unable to construct the climate measures for more recent years because of data limitations. Due to the historical focus of the GHCN-D, the number of available weather stations in Mexico drops from an average of n=182 to n=15 for more recent years, rendering interpolations of climatic data after 1999 unstable. However, during the study period, Mexico experienced a major increase in temperature and associated drought conditions (Stahle et al. 2009) that make this period particularly useful for studying climate related migration patterns. We do not use migration information before 1986 due to a profound change in the Mexico-U.S. migration regime with the enactment of IRCA in 1986 (LoBreglio 2004).

Outcome Variable

In the MMP, migration is defined as a move that involved a change in usual residence, excluding short trips for visits, commuting, shopping or vacation (Fussell 2004). We investigate the first move from within a household, based on the assumption that the first move is a livelihood strategy more directly related to environmental factors compared to later moves (Henry et al. 2004; Nawrotzki et al. 2015b).[3] For each household, we obtain all years during which any household member left for the U.S. and select the earliest year. Using the information on the year of the first move, we then constructed a household-year dataset (risk set) in which each row indicates whether a household had sent a member to the U.S. in a given year during the study period (1986-99). Households are considered at risk of a first move if they had not sent a member to the U.S. prior to the year 1986. Households enter the risk set when they are formed (approximated by the date of current union formation) and the household head is at least 15 years of age. Households leave the risk set when the household head turns 65, the end of the study period is reached in 1999, or when the household is censored after the survey year.[4] We also account for domestic migration into and out of the study communities, and expose households to the risk of migration only if at least one core household member (head or spouse) was present in the community. However, our sample does not include members of entire households that emigrated to the U.S. prior to the survey year.[5] Figure 3 visually displays the hazard of migration across the

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[3]The first international migration can be considered a major event that is remembered with reasonable accuracy by most household members. As such, use of the first migration has the added benefit of guarding against recall bias.

[4]The phenomenon that households leave the data set after the year they are surveyed is known in the event-history literature as "right censoring". We retain right censored cases in the analysis based on the assumption that the censoring is non-informative, meaning that the time of migration is independent of the time a particular community was surveyed (Allison 1984; Steele 2005).

study period. The trend in the migration hazard follows changes in the Mexican economy. Higher levels of migration are associated with economic crises and recessions, as reported for the periods of 1988-89 (Lustig 1990) and 1994-95 (McKenzie 2006). In addition, adjustments in border policies and programs reportedly added to the higher numbers of Mexico-U.S. migration during the late 1980s (Martin 1990).

Primary Predictor Variables

In an attempt to standardize the use of climate measures, the Expert Team on Climate Change Detection and Indices (ETCCDI)[6] developed a suite of 27 core indices for the Intergovernmental Panel on Climate Change (IPCC)'s Third Assessment Report (Peterson et al. 2001; Peterson and Manton 2008). For the present analysis, we selected the warm spell duration index (wsdi) and the number of days of heavy precipitation (r10mm) from among the suite of core ETCCDI indices (for a definition of the climate change measures see Appendix A). We selected these indices because (1) they tap two climatic dimensions of temperature and precipitation, (2) measure climatic extremes rather than changes in average conditions, (3) were only moderately correlated and, so, permit joint inclusion in the models, and (4) have been shown to be associated with migration behavior in prior research (Nawrotzki et al. 2015b). In order to compute the climate change measures, four steps were necessary: (1) missing data imputation, (2) computation of climate measures at each station, (3) spatial interpolation to obtain values for unmeasured municipalities, and (4) relating annual climate measures to a 30-year reference period to approximate change.

The time series of daily temperature and precipitation records in the GHCN-D dataset is not complete. About 20% of the records are missing because of instrumentation errors, failure of recording, or poor data quality (cf., Menne et al. 2012). The computation of the ETCCDI measures requires a complete time series. Consequently, we employed Multiple Imputation (MI) (Allison 2002; Rubin 1987) to impute missing data. Through the introduction of random variation, MI accounts for uncertainty in the imputation procedure (Honaker and King 2010; Little and Rubin 2002). We employed the R package *Amelia* (Honaker et al. 2011), which is capable of capturing seasonal trends through explicit inclusion of a polynomial for time in the imputation model.[7]

In the next step, we employed the complete time series of temperature and precipitation readings to compute the two ETCCDI climate change measures using the R package *climdex.pcic*, managed and released by the Pacific Climate Impacts Consortium (Bronaugh 2014). The ETCCDI measures were calculated as annual aggregates for each weather station. Weather stations frequently fall outside of MMP municipalities for which climate

[5]While this omission could bias our estimates, the amount of error is likely to be small in rural areas where migrants are more likely to return (Cornelius 1992; Riosmena 2004). In addition, when the permanent relocation of the entire household was related to climate impacts, then the resulting sample of households will be less sensitive to climate shocks. In this way, the presented results can be considered conservative and likely underestimate the magnitude of the true climate-migration response.
[6]The expert team is jointly sponsored by the World Meteorological Organization (WMO) Commission for Climatology (CCl), the World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR), and the Joint WMO-Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) Technical Commission for Oceanography and Marine Meteorology (JCOMM).
[7]Inspection of density, overimputation, and overdispersion plots, suggested accurate performance of the imputation model (Honaker et al. 2011).

measures are required. Consequently, we employed geostatistical methods to obtain values at unknown locations. Specifically, we used cokriging interpolation because it allows the inclusion of covariates in the interpolation model.[8] Since temperature and precipitation are correlated with altitude, we refined the interpolations by including information on elevation using a digital elevation model (DEM).[9] The cokriging model produces a continuous surface of interpolated values. Using a lattice of points (700×700 meters mesh size), we extracted values that fall within each municipality, and assigned each household the respective municipality mean value.[10]

Finally, we computed relative change measures by relating the value of each observation year to a 30-year long-term average (1961-90). The resulting change measures were then standardized (divided by the standard deviation) in order to make the climate measures comparable. Figure 4 displays the average trajectory of the two ETCCDI climate measures over the study period.

The trajectory for warm spell duration reflects general warming trends, as anticipated by future projections (IPCC 2013). For much of Mexico, the late 1990s were exceptionally warm years (Stahle et al. 2009), and the positive slope testifies to this trend. Although precipitation remained slightly below the long term mean for most of the study period, no clear trend could be discerned, a finding in line with climate patterns for other world regions (Klein Tank et al. 2006).

Control Variables

The climate represents only one of several factors influencing migration decisions (Black et al. 2011a; Black et al. 2013; de Haas 2011; Findlay 2011; Hunter et al. 2015; McLeman 2011). As such, it is necessary to control for various socio-demographic factors that influence households' migration decisions (Brown and Bean 2006). Given our understanding of migration as a household-level livelihood strategy, we group control variables into types of livelihood capitals (social, human, physical, financial, natural) in line with the sustainable livelihoods framework (Carney et al. 1999; Scoones 1999). The control variables operate at the household and the municipality levels, and were included as time-varying and time-constant predictors. Table 1 provides summary statistics and source information for all variables employed in the present analysis.

At the household level, two variables capture social capital. A dummy variable reflects whether the household head was female (1 = yes) and whether the household head was married (1 = yes). In Mexican society, males and females have different access to various forms of social capital, translating into distinct migration dynamics (Kanaiaupuni 2000).

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[8]Cokriging is based on regionalized variable theory (Matheron 1971), and uses the spatial trend and local spatial autocorrelation to inform predictions (Bolstad 2012; Hevesi et al. 1992). Cokriging has been frequently used to interpolate climate measures (e.g., Aznar et al. 2013; Garzon-Machado et al. 2014).

[9]With a 1-kilometer grid cell resolution, the DEM is based on remotely sensed images from the Shuttle Radar Topography Mission (SRTM), created and released by the U.S. Geological Survey (USGS) and the National Geospatial-Intelligence Agency (NGA) (Danielson and Gesch 2011).

[10]We tested the accuracy of the cokriging procedure by using a bootstrap split-sample method in which 10% of the stations were omitted from the interpolation and error values were computed at known locations. The low magnitude of error values and random distribution across space suggests that the interpolations produced reliable results.

Marriage expands social networks from one to two families such that households may be able to access support from a larger kinship network in times of environmental hardship (Abu et al. 2014). To measure human capital, we constructed a variable indicating the number of young children (age < 5 years) present in the household during each observation year. Other variables measure the educational attainment of the household head with respect to years of schooling completed, as well as cumulative work experience. In addition, a set of dummy variables indicate whether the household head was employed in a blue- or white-collar occupation or was unemployed/not in the labor force during the observation years. Physical capital was captured by two dummy variables indicating whether a household owned property or a business.

At the municipality level, we approximate migration network effects using a variable for the percentage of adults in a community with migration experience (Massey et al. 1994). In many developing countries, income is received in monetary and non-monetary forms and often varies seasonally (Montgomery et al. 2000). Hence, the possession of assets and access to various services constitute a more stable measure of household wealth and has been frequently used in prior research (Hunter et al. 2014; Mberu 2006; Nawrotzki et al. 2013; Nawrotzki et al. 2015b). Accordingly, we constructed a standardized wealth index (Cronbach's alpha = 0.85) that combines 10 variables measuring housing quality (material of floor, wall, roof, number of rooms and bedrooms, and toilet type) and service and infrastructure access (water supply, electricity, sewage system, and cooking fuel type).

To capture the overall level of agricultural dependence of each municipality, we employed a measure of the corn area harvested around the year 2000, derived from the Terra Populus data access system (Kugler et al. 2015; MPC 2013b). However, agricultural dependence does not necessary imply vulnerability to climate change if technology (e.g., irrigation) can be used to guard against adverse climatic impacts. We, therefore, added a measure of the percentage of irrigated farmland in 2003.[11] Also important are the general climatic conditions, as an increase in temperature will likely have different impacts in a hot dry climate compared to a cold humid climate (Nawrotzki et al. 2013). We therefore included a measure of the average precipitation and average temperature during the baseline period of 1961-90 in all models. Finally, a measure of the percentage of the male labor force employed in the agricultural sector serves as a proxy for reliance on climate sensitive sectors for income generation.[12]

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[11]Unfortunately, measures of corn area harvested and percent irrigated farmland are only available for years after our study period. These variables were included to account for general differences in agricultural dependence and infrastructure availability. In our attempt to investigate changes in irrigation infrastructure, we were able to obtain a partial time series of the percent farmland irrigated for 25 of our 68 municipalities between 1994 and 2003. The average change in the proportion of farmland irrigated over this period was +0.003% (SD=7.27%), and ranged from a minimum of −24.7% to a maximum of +14.43%. As such, the use of time-invariant measures to approximate historic conditions results in some uncertainty and the coefficient estimates should be interpreted with cautions.

[12]Information on the percentage of adults with migration experience, the wealth index, and the percentage of male labor force employed in the agricultural sector was available at decadal time steps. For these measures we employed linear interpolation to obtain semi time-varying predictor, as recommended by the event history literature (Allison 1984).

Estimation Strategy

Both migration and climate change are time dependent phenomena best captured by longitudinal models. In line with prior research (Gray and Bilsborrow 2013; Henry et al. 2004; Hunter et al. 2013; Mueller et al. 2014), we employ discrete-time event history models for this study (Allison 1984; Singer and Willett 2003; Steele 2005). Since households are nested within municipalities, we use a multi-level version of the event history models (Barber et al. 2000; Steele et al. 1996; Steele et al. 2004). Equation 1 provides a formal description of the model.

$$logit\left(h_{ijk}\right) = \alpha + \beta_1\left(wsdi_{ik}\right) + \beta_2\left(r10mm_{ik}\right) + \sum\nolimits_{n=3}^{y}\beta_n\left(x_{nz}\right) + u_k \quad (1)$$

Eq. 1 expresses the logit hazard of international migration for a given household j located in municipality k during period i. The probability of a household-level move is a function of the baseline hazard α, the effect (β_{1-2}) of the climate change measures (warm spell duration index = $wsdi_{ik}$, number of days heavy precip = $r10mm_{ik}$) and the effects (β_{n-y}) of various control variables (x_{nz}). The baseline hazard α was included as a set of year dummy variables to allow for the most flexible treatment of time (Singer and Willett 2003).[13] The control variables are time-varying and time-constant and operate at both the household and municipality level, which is reflected by the generic subscript z. Although migrants remember the year of migration with considerable accuracy (Massey et al. 1987), we account for residual recall bias by controlling for the survey year in all models. The parameter u_k constitutes the municipality-level random effects term, which accounts for the clustering of households within municipalities.

We include both climate change measures in one model to obtain unbiased estimates, controlling for both temperature and precipitation effects (Auffhammer et al. 2013). To reflect the effect of a precipitation decline (instead of increase) in the regression coefficient for $r10mm$, we inverted the standardized measure of number of days heavy precip (multiplication by −1) prior to inclusion in the models. To guard against endogeneity, we lagged all control variables by one year (cf., Gray 2009, 2010).

To explore the timing of a climate related move, we estimated seven separate models in which the climate change measures were lagged between one and seven years. The subscript ik of the climate change measures indicates that these variables represent time-varying municipality-level measures. Prior research has shown that the two-level multi-level structure is suitable for the inclusion of time-varying context-level measures (Barber et al. 2000). We use the *lme4* package (Bates 2010; Bates et al. 2014) within the R statistical environment (RCoreTeam 2015) to fit the multi-level event history models.[14]

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[13]The year dummy variables account for unobserved changes, including policy changes, economic cycles, political events, technological advancements, and other climate shocks and natural disasters (Bohra-Mishra et al. 2014).
[14]For increased speed and improved convergence properties we used the integer scalar setting of nAGQ = 0 so that the random-effects and the fixed-effects coefficients were optimized (optimizer = "bobyqa") in the penalized iteratively reweighted least squares step (Bates et al. 2014).

Results and Discussion

As the first step in our analysis, we explore the effects of the two climate predictors on international migration for a fixed lag time of one year, using various model specifications (Table 2). We compared an ordinary event history model (without random effects) without and with time dummies (specifications A and B). We then expanded the ordinary event history model to a multilevel event history model containing random municipality effects without and with time dummies (specifications C and D), and subsequently added household (specification E) and municipality controls (specification F).[15] Table 2 also reports results adding the climate predictors individually (specifications F1 and F2) and jointly (specification F3) to the fully adjusted model. The results reveal that the coefficient estimates are highly robust to various model specifications. The parameter estimates show important impacts of temperature extremes on international migration, while changes in precipitation extremes have no discernable effects. This observation is in line with prior research, demonstrating that migration is more strongly influenced by temperature than precipitation effects (Bohra-Mishra et al. 2014; Mueller et al. 2014). An increase in warm spell duration by one standard deviation unit increases the odds of a first international move by 11% (Odd Ratio [OR]=1.11). In rural agriculturally dependent communities, an increase in warm spell duration likely has detrimental effects on farm production and crop yields. For example, corn, as the main staple crop in Mexico (Keleman et al. 2009), is highly sensitive to heat stress, and an increase in temperature has been shown to lead to a strong decline in yields (Lobell and Field 2007). When adverse climate change undermines livelihood stability, households may choose to send a member to a destination where climate and market conditions are uncorrelated with those at home to guarantee a stable income through remittances (Massey et al. 1993).

To explore the timing of the climate migration response, we built on the fully adjusted model (Table 2, specification F3) and lagged the climate predictors between one and seven years (Table 3, Fig 5). Lag time represents the temporal distance (in years) between the climate shock and the migration response.

Consistent with our third hypothesis, the risk of migration is low immediately following a climate shock and increases thereafter, peaks about three years out, and subsequently declines.[16] After a climate shock, households initially pursue and cycle through short-term coping and *in-situ* adaptive strategies (Berkes and Jolly 2002; Dow et al. 2013; IPCC 2012; McLeman 2011). Failure to successfully adapt *in-situ* leads households to consider migration as viable alternative livelihood strategy, as indicated by the increase in strength in the climate-migration association during the first three years after a climate shock. However, through a process of trial and error that involves learning about *in-situ* adaptive strategies available to them, households become increasingly proficient in adapting *in-situ* (cf., Marra et al. 2003), thereby more successfully responding to climate shocks in their place of

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[15]Appendix B reports a correlation matrix (Table 4) as well as the parameter estimates for household and municipality control variables (Table 5) included in the fully adjusted multilevel event history model.
[16]We observed similar results for various other ETCCDI indices, including the % warm days (tx90p), the number of frost days (fd), the temperature during the coldest day (txn), the % cool nights (tn10p), and the total wet-day precipitation (prcptot). Results from different measures serve as a robustness test, suggesting that the reported functional form reflects a general pattern.

residence. Consequently, after peaking about three years after a climate shock, the risk of migration decreases, as evidenced by the decline in the strength of the climate-migration association for later years.

The directionality of significant effects suggests that an increase in temperature and a decline in rainfall are problematic for rural livelihoods, leading to increased mobility during certain years (Bohra-Mishra et al. 2014; Hunter et al. 2013; Mueller et al. 2014; Nawrotzki et al. 2013).[17] As we noted earlier, corn, the main staple crop in Mexico (Keleman et al. 2009), is highly sensitive to heat stress, which has negative implications for corn yields (Lobell and Field 2007). Likewise, given that only a fraction of farmland in Mexico is irrigated (Carr et al. 2009), sufficient rainfall is important for positive harvest outcomes (Lobell and Field 2007). Water stress may lead to substantial yield losses (Cakir 2004), resulting in adverse livelihood effects to which households may respond with increased migration levels (Warner and van der Geest 2013).

The lower magnitude of the precipitation related migration response and larger number of insignificant relationships is likely due to the fact that, relative to temperature increases, many more *in-situ* adaptation options are available to farmers to deal with precipitation declines. These measures are often comparatively easy to implement, and may include installation of irrigation systems or changes in tillage methods to increase soil water retention (Howden et al. 2007; Luers et al. 2003).

In sum, for both temperature and precipitation shocks, we observe an initial increase in the risk of migration, followed by a decline, a pattern which can best be described as a delayed response with successful transition to *in-situ* adaptation (see Fig 1, Panel C).

Conclusion

Using two indicators of climate shocks, this study confirms prior research, providing evidence that an increase in temperature and decline in precipitation lead to elevated risks of migration (Gray and Bilsborrow 2013; Hunter et al. 2013; Mueller et al. 2014). However, the unique contribution of this paper is a detailed investigation, theoretically and empirically, of the timing of climate related moves. Our results reveal a pattern of an increase followed by a decrease in the strength of the climate-migration association after a climate shock. We explain this pattern with reference to a mix of *in-situ* and *ex-situ* (migration) adaptation strategies employed by households to alleviate climate-related livelihood insecurities. Households prefer to adapt in place (Findlay 2011), but revert to migration to stabilize livelihoods if *in-situ* adaptation strategies fail to produce the desired results. Consequently, we witness an initial increase in the strength of the climate-migration association. However, over time, through a process of trial and error, households are eventually successful in navigating and implementing *in-situ* adaptation strategies, and gradually reduce their use of migration. Consequently, the strength of the climate-migration association begins to decline.

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[17]The coefficients for "No. days heavy precip" reflects the effect of a one standard deviation *decrease* in precipitation.

Although carefully conducted, this study is not without limitations. First, our theoretical models draw on assumptions regarding the success and failure of implementing *in-situ* adaptation strategies. Although grounded in relevant theoretical and empirical literatures, our data do not permit a direct test of this dynamic. Future research may therefore complement our study of *ex-situ* (migration) responses with detailed empirical investigations of specific *in-situ* responses to climate shocks. Second, our results are strictly generalizable only to the rural MMP communities from which the data were drawn. Although studies suggest that the MMP accurately capture general patterns of Mexican migration (Massey and Capoferro 2004; Massey and Zenteno 2000), future research may validate our findings using census data and other data sources. Third, the statistical procedures of spatial interpolation, as well as missing data imputation, may have resulted in data smoothing and an underestimation of the true variation. However, multiple robustness checks (e.g., bootstrap split-sample procedures) suggest a high degree of accuracy of the employed measures.

Despite these limitations, our study contributes in important ways to our understanding of climate shocks and the timing of migration. Specifically, going beyond knowledge *that* a lagged pattern characterizes the climate-migration relationship, we provided empirical evidence for a lagged migration response with a successful transition to *in-situ* adaptation. Our findings have important policy implications. The two-phased nature of the climate-migration relationship suggests that households pursue and attempt to adopt *in-situ* adaptation strategies early in the process of responding to a climate shock, but that some of these strategies may fail. When climate change effects are detected, policy makers should therefore consider implementing programs that assist rural Mexicans in successfully navigating and implementing *in-situ* adaptation strategies, in addition to ensuring that options are available and of sufficient quality. Such programs will be most effective if implemented early (versus late) in the climate change adaptation stage when the risk of migration starts to increase. Livelihood-based adaptation programs may prove to be more effective in reducing Mexico-U.S. migration than expensive border fortification efforts that have been shown to be of limited success (Angelucci 2012). With these policy implications in mind, the work in this paper should be considered as a starting point for more nuanced theoretical and empirical analyses to shed light on the timing of migration after a climate shock.

Acknowledgements

Appendix

A. Definition of climate measures

Warm spell duration index (wsdi)

The warm spell duration index is defined as the annual count of days when at least six consecutive days surpassed the 90th percentile of the maximum temperature of the baseline period (1961-90). Let TX_{ij} be the daily maximum temperature on day i in period j and let $TX_{in}90$ be the calendar day 90th percentile centered on a 5-day window for the base period 1961-90. The warm spell duration can then be computed as the period specific count of days N_j with at least 6 consecutive days where $TX_{ij} > TX_{in}90$ (Eq. 2).

$$wsdi_j = N_{j\left(TX_{ij} > TX_{in}90, N \geq 6\right)} \quad (2)$$

No. days heavy precip (r10mm)

The No. of days of heavy precipitation is defined as the annual count of days with more than 10 mm of precipitation. Let RR_{ij} be the daily precipitation amount on day i in period j. The number of days with heavy precipitation is then computed as the count of days N where RR_{ij} 10mm (Eq. 3).

$$r10mm_j = N_{\left(RR_{ij} \geq 10mm\right)} \quad (3)$$

For a full list of ETCCDI indices and their technical definitions see http://etccdi.pacificclimate.org/list_27_indices.shtml

B. Correlation matrix and parameter estimates of control variables

Table 4

Correlation matrix of outcome and substantive predictor variables employed in the investigation of the timing of international migration in response to climate shocks from rural Mexico, 1986-99

	Migrant	Female	Married	No. of children	Education	Working experience	Occupation: not in labor force	Occupation: white collar	Owns property	Owns business	International migrants	Wealth index	Corn (area harvested)	Farmland irrigated	Base period precip (1961-90)	Base period temp (1961-90)	Male labor in agriculture	Warm spell duration index	No. days heavy precip
Migrant	1.00																		
Female	-0.02	1.00																	
Married	0.00	-0.37	1.00																
No. of children	0.00	-0.14	0.14	1.00															
Education	0.00	-0.13	0.06	0.07	1.00														
Working experience	-0.03	0.03	0.06	-0.35	-0.43	1.00													
Occupation: not in labor force	-0.01	0.61	-0.17	-0.13	-0.12	0.07	1.00												
Occupation: white collar	-0.02	-0.03	0.04	0.01	0.44	-0.11	-0.10	1.00											
Owns property	-0.02	-0.01	0.12	-0.07	-0.09	0.31	-0.10	0.01	1.00										
Owns business	-0.01	0.00	0.02	-0.05	0.05	0.08	-0.10	0.14	0.09	1.00									
International migrants	0.08	0.07	-0.02	-0.03	-0.07	0.08	0.05	-0.01	-0.05	0.00	1.00								
Wealth index	0.02	0.04	0.03	-0.08	0.03	0.03	0.04	-0.03	0.04	-0.04	0.19	1.00							
Corn (area harvested)	-0.01	-0.01	0.04	0.01	0.01	-0.04	0.00	-0.06	-0.01	-0.03	-0.15	0.29	1.00						
Farmland irrigated	0.00	0.00	0.04	-0.02	-0.03	-0.01	0.00	0.02	0.04	-0.01	0.02	0.16	0.04	1.00					
Base period precip (1961-90)	-0.02	-0.01	-0.06	-0.03	0.04	0.01	0.00	0.03	-0.01	0.03	-0.29	-0.41	-0.16	-0.32	1.00				
Base period temp (1961-90)	-0.03	-0.02	0.02	0.01	0.06	-0.04	0.06	0.06	-0.02	0.06	-0.12	-0.33	-0.21	-0.08	0.62	1.00			
Male labor in agriculture	0.00	-0.07	-0.01	0.01	-0.08	0.03	-0.04	-0.03	0.00	0.03	-0.16	-0.40	-0.17	0.07	0.22	0.24	1.00		
Warm spell duration index	0.01	-0.02	-0.01	-0.10	0.08	0.06	-0.02	0.02	0.09	0.05	-0.16	0.28	0.09	0.01	0.11	0.04	-0.11	1.00	
No. days heavy precip	0.00	0.02	-0.02	-0.02	0.00	0.00	0.01	0.00	0.01	-0.01	-0.01	0.24	0.09	0.06	-0.19	-0.20	-0.09	0.09	1.00

The decision to migrate is influenced by various socio-demographic factors (Brown and Bean 2006). Table 5 shows multi-level event history models, including only household level variables (Model 1), and then adding municipality level predictors (Model 2). In

Table 5

Parameter estimates derived from multilevel event-history models for household and municipality control variables to predict international migration from rural Mexico, 1986-99

	Model 1		**Model 2**	
	b	**sig.**	**b**	**sig.**
Household level (head)				
Female	0.56	***	0.54	***
Married	0.97		0.98	
No. of children	0.90	**	0.91	**
Education [a]	0.92		0.90	
Working experience [a]	0.75	***	0.74	***
Occupation: not in labor force	0.99		0.97	
Occupation: white collar	0.53	***	0.54	***
Owns property	0.85	*	0.86	*
Owns business	0.78	*	0.79	*
Community/municipality level				
International migrants [a]			1.50	***
Wealth index			1.15	
Corn (area harvested)			0.93	
Farmland irrigated [a]			1.03	
Base period precip (1961-90)			1.18	
Base period temp (1961-90)			0.90	**
Male labor in agriculture [a]			1.05	
Model statistics				
Var. Intercept (Mun)	0.502		0.276	
BIC	9323		9339	
N (HH-year)	67508		67508	
N (HH)	7062		7062	
N (Mun)	68		68	

Notes: Coefficients reflect odd ratios; all predictors were lagged by one year; models control for baseline hazard by using period fixed effects (not shown); models control for survey year to account for recall bias (not shown)

[a] coefficients refer to an incremental change of 10 units; reference group for occupation: blue collar; low values on the Variance Inflation Factor (VIF < 2.7) suggest that multi-collinearity does not bias the estimates

*
p<0.05
**
p<0.01
***
p<0.001

line with much prior work on Mexican migration, the models suggest that the typical migrant household is male headed (Lindstrom and Lauster 2001), has few young children (Massey and Riosmena 2010; Nawrotzki et al. 2013), is employed in a blue collar occupation with limited work experience (Fussell 2004; Massey et al. 1987), and does not

own property or a business (cf., Massey and Parrado 1998). Only a few municipality characteristics influence the probability to migrate. The probability to migrate is strongly elevated for communities with large proportions of adults with prior international migration experience, testifying to the importance of social networks (Fussell 2004; Massey and Espinosa 1997; Massey et al. 1994). In addition, households are less likely to migrate from areas with historically warm temperatures, which likely reflects that most migrants come from the cooler west-central parts of Mexico, instead of the hot arid northern border states (Hamilton and Villarreal 2011).

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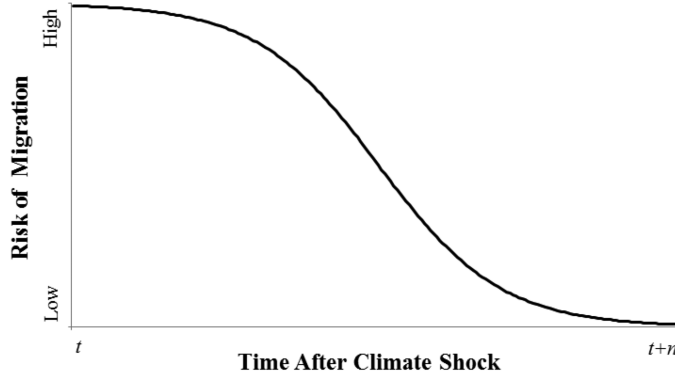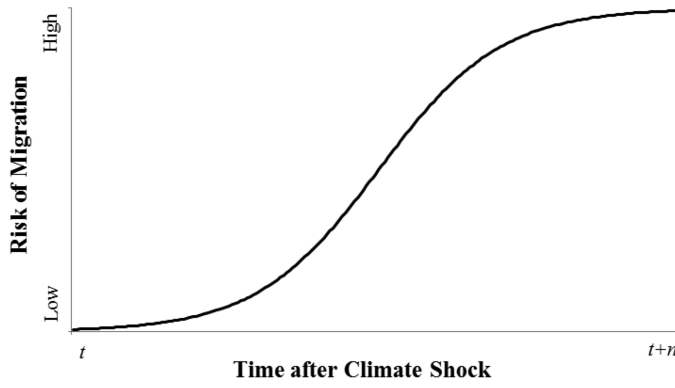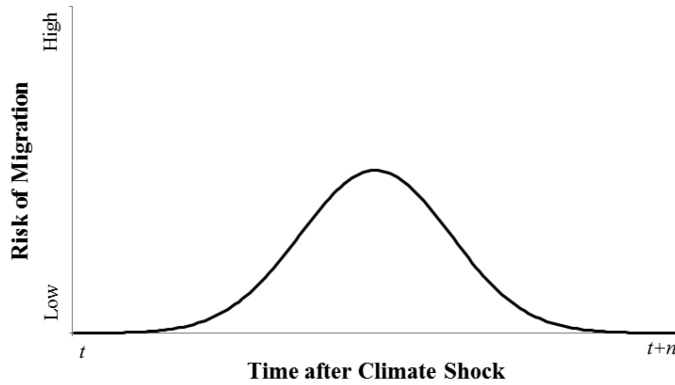
Panel A: Immediate response


Panel B: Delayed response

**Panel C: Delayed response – transition to *in-situ* adaptation**

Fig 1.
Theoretical models depicting the risk of migration after a climate shock
Note: Figures depict stylized representations of the complex relationships between climate shocks and migration across time; t = time lag between climate shock and migration response ranging from 1 to n years.
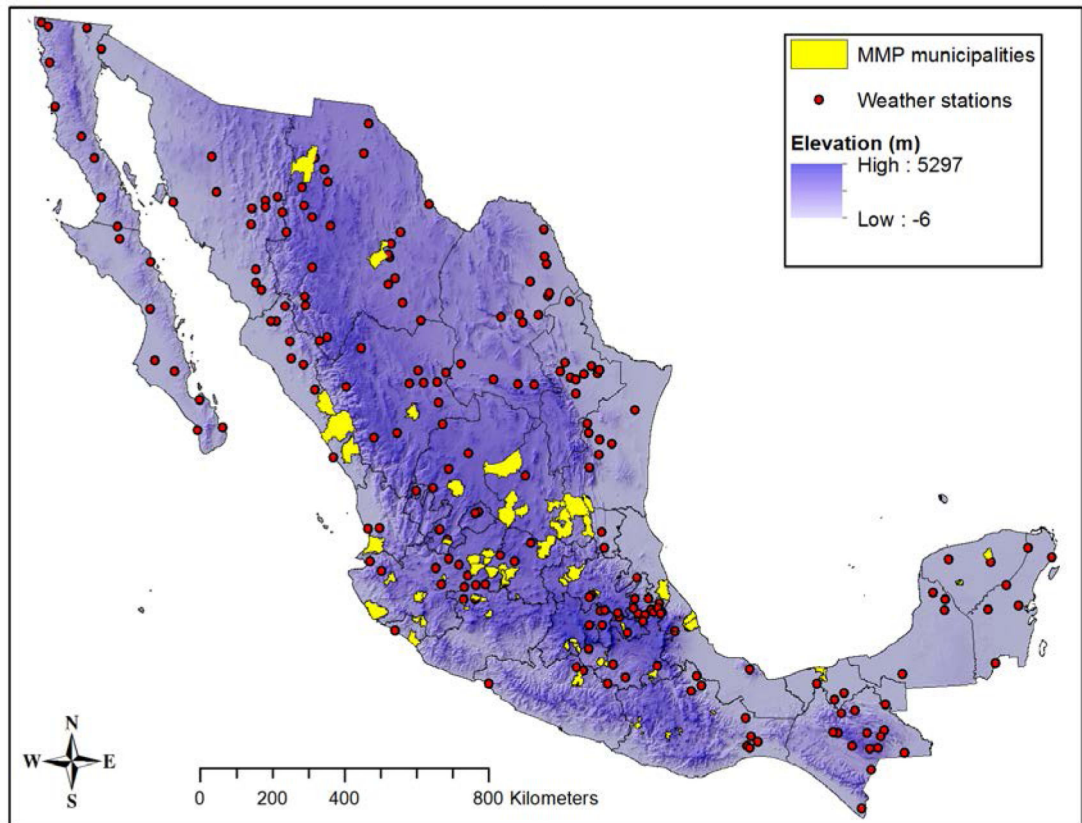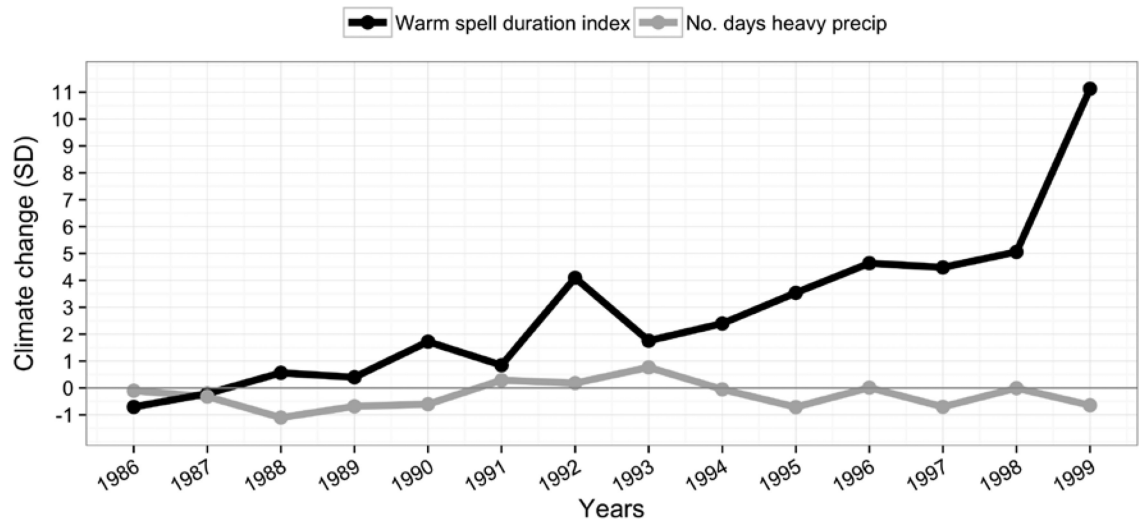
Fig 2.
Geographic location of rural MMP municipalities and spatial distribution of weather stations across Mexico

Note: rural municipalities: n = 68
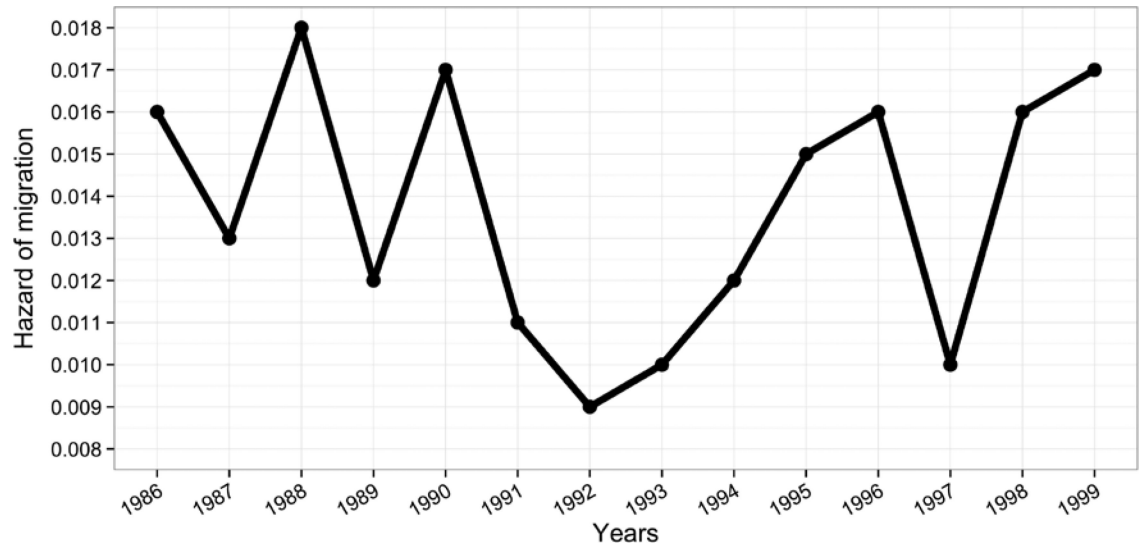
Fig 3.
Hazard of international migration from rural MMP communities

Fig 4.
Trend in climate measures over the study period (1986-99) for rural MMP municipalities

Note: Displayed climate measures were lagged by one year.
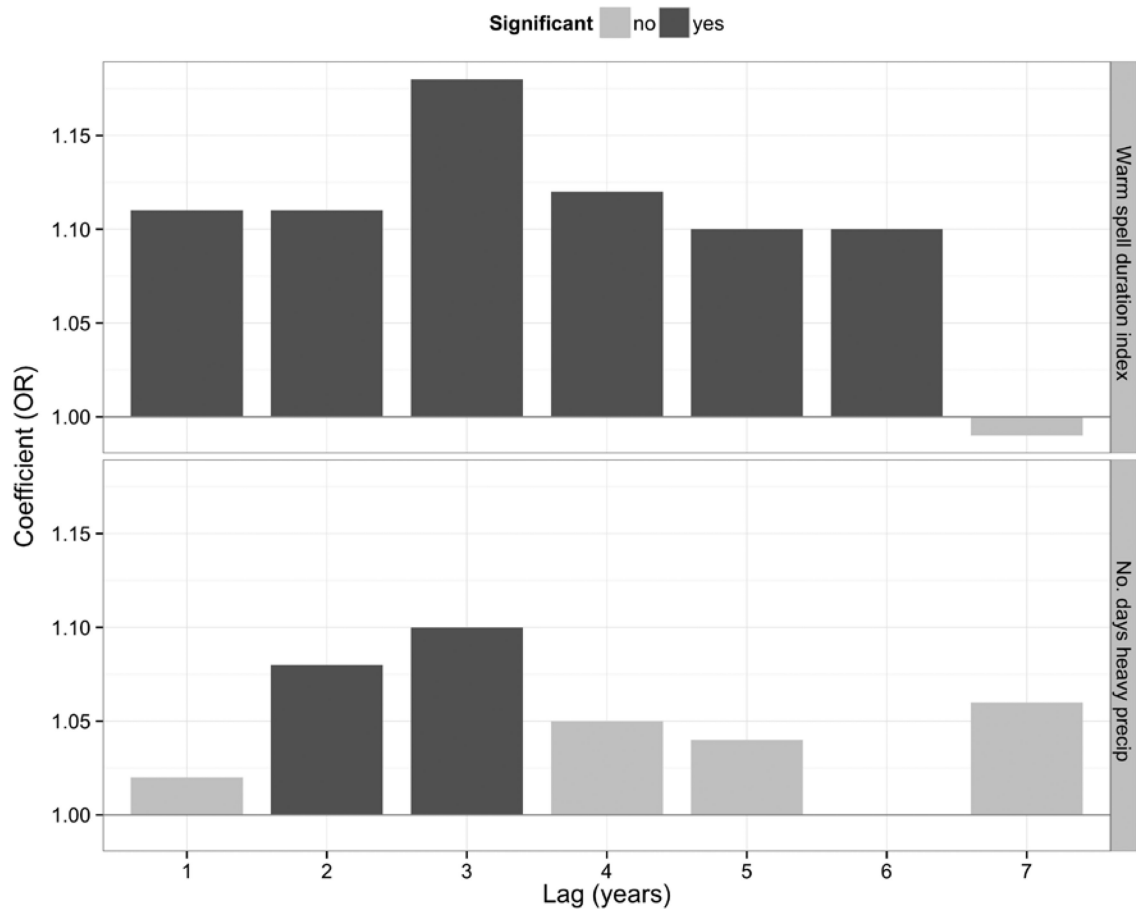
Fig 5.
Visual representation of the odds of international outmigration from rural Mexico in
response to the influence of climate shocks for various time lags
Note: Lag n (n = 1...7) reflect the number of years (n) between the climate signal and the
year (t) during which migration was observed; the coefficients for "No. days heavy precip"
reflects the effect of a one standard deviation *decrease* in precipitation.

Table 1

Descriptive statistics of variables employed in the analysis of the timing of a climate related international move from rural Mexico, 1986-99

	Unit	TV	Source	Mean	SD
Household level (head)					
Social capital					
Female	1|0	No	MMP	0.14	0.35
Married	1|0	Yes	MMP	0.8	0.4
Human capital					
No. of children	Count	Yes	MMP	0.85	1.04
Education	Years	Yes	MMP	5.34	4.28
Working experience	Years	Yes	MMP	24.93	12.34
Occupation: not in labor force	1|0	Yes	MMP	0.09	0.29
Occupation: blue collar	1|0	Yes	MMP	0.82	0.39
Occupation: white collar	1|0	Yes	MMP	0.09	0.29
Physical capital					
Owns property	1|0	Yes	MMP	0.7	0.46
Owns business	1|0	Yes	MMP	0.16	0.36
Community/municipality level					
Social capital					
International migrants	%	Yes	MMP-C	15.16	14.5
Financial capital					
Wealth index	z-values	Yes	IPUMS-I	−0.79	0.39
Natural capital					
Corn (area harvested)	sqm/10ha	No	TerraPop	1.26	1.11
Farmland irrigated	%	No	INEGI	23.68	25.76
Base period precip (1961-90)	mm/day	No	GHCN-D	2.83	1.34
Base period temp (1961-90)	deg. C	No	GHCN-D	21.07	2.93
Economic environment					
Male labor in agriculture	%	Yes	MMP-C	56.14	17.66
Climate change					
Warm spell duration index	z-values	Yes	GHCN-D	2.32	3.16
No. days heavy precip	z-values	Yes	GHCN-D	−0.23	1.28

Note: TV = time varying; Source information: MMP = Mexican Migration Project data available from http://mmp.opr.princeton.edu/; MMP-C = COMMUN supplementary file of MMP; IPUMS-I = Mexican census data (1% extract) obtained via Integrated Public Use Microdata Series – International (MPC 2013a; Ruggles et al. 2003); TerraPop = Terra Populus data access system (Kugler et al. 2015; MPC 2013b); INEGI = data obtained from Instituto Nacional de Estadística y Geografia (INEGI 2012); GHCN-D = data derived from the Global Historical Climate Network – Daily (Menne et al. 2012).

Table 2

Alternative specifications of the effects of climate shocks on international migration from rural Mexico, 1986-99

Specification	Warm spell duration index		No. days heavy precip	
	b	sig.	b	sig.
A Ordinary EHM	1.02	*	1.03	
B Ordinary EHM + Time	1.08	***	1.02	
C Multilevel EHM	1.08	***	1.04	
D Multilevel EHM + Time	1.10	***	1.03	
E Multilevel EHM + Time + HH	1.10	***	1.03	
F1 Multilevel EHM + Time + HH + Muni	1.11	***	--	--
F2 Multilevel EHM + Time + HH + Muni	--	--	1.03	
F3 Multilevel EHM + Time + HH + Muni	1.11	***	1.02	

Note: Coefficients reflect odd ratios; EHM = Event history model; Time = time control variables including period fixed effects and the survey year; HH = Household control variables (as shown in Appendix Table 5); Muni = Municipality control variables (as shown in Appendix Table 5); all predictors and controls were lagged by one year; specifications F1 and F2 include either "Warm spell duration index" or "No. days heavy precip" individually, while F3 includes both climate predictors jointly; the coefficient for "No. days heavy precip" reflects the effect of a one standard deviation *decrease* in precipitation;

**
  p<0.01

*
  p<0.05

***
  p<0.001

Table 3

Odds of international outmigration from rural Mexico in response to the influence of climate shocks for various time lags

	Lag 1		Lag 2		Lag 3		Lag 4		Lag 5		Lag 6		Lag 7	
	b	sig.	b	sig.	b	sig.	b	sig.	b	sig.	b	sig.	b	sig.
Warm spell duration index	1.11	***	1.11	***	1.18	***	1.12	***	1.10	**	1.10	**	0.99	
No. days heavy precip	1.02		1.08	*	1.10	**	1.05		1.04		1.00		1.06	

Note: Coefficients are reported in odds ratios; estimates derived from fully adjusted multilevel event history models controlling for various household and municipality factors (Table 2, Specification F3); the coefficient for "No. days heavy precip" reflects the effect of a one standard deviation *decrease* in precipitation; Lag n (n = 1...7) reflect the number of years (n) between the climate signal and the year (t) during which migration was observed; a jackknife-type procedure was performed, omitting one municipality at a time from the sample (Nawrotzki 2012; Ruiter and De Graaf 2006). The results demonstrated that the estimates were highly robust;

*
p<0.05

**
p<0.01

***
p<0.001