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Internal and International Mobility as Adaptation to Climatic Variability in Contemporary Mexico: Evidence from the Integration of Census and Satellite Data

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Abstract

Migration provides a strategy for rural Mexican households to cope with, or adapt to, weather events and climatic variability. Yet prior studies on "environmental migration" in this context have not examined the differences between choices of internal (domestic) or international movement. In addition, much of the prior work relied on very coarse spatial scales to operationalize the environmental variables such as rainfall patterns. To overcome these limitations, we use fine-grain rainfall estimates derived from NASA's Tropical Rainfall Measuring Mission (TRMM) satellite. The rainfall estimates are combined with Population and Agricultural Census information to examine associations between environmental changes and municipal rates of internal and international migration 2005–2010. Our findings suggest that municipal-level rainfall deficits relative to historical levels are an important predictor of both international and internal migration, especially in areas dependent on seasonal rainfall for crop productivity. Although our findings do not contradict results of prior studies using coarse spatial resolution, they offer clearer results and a more spatially nuanced examination of migration as related to social and environmental vulnerability and thus higher degrees of confidence.

1 Introduction

Migration has historically been used by households and communities to cope with, or adapt to, direct and indirect impacts of weather events such as damage to property and crops (Gutmann and Field, 2010; McLeman and Hunter, 2010; López-Carr, 2012). Since severe

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weather events may become more likely with continued climate change (Parry, 2007; Field et al., 2014)[1], migration may become a more commonly employed coping mechanism (e.g., McLeman,2013; Warner et al., 2012; Magrin et al., 2014 for South America) with important consequences for individual households and the community. Therefore, it is critical to shed light on the ways weather events or changes in weather patterns can fuel existing migration systems, and thus develop improved understanding of the migration-environment association.

Mexico is an important context to study given strong and longstanding migration out of rural areas, both towards internal urban destinations as well as to the United States (Garza, 2003; Durand et al., 2001). Indeed, the environment-migration association has been explored somewhat intensively in recent years (e.g., Feng and Oppenheimer, 2012; Hunter et al., 2013; Nawrotzki et al., 2013) but there are several aspects that remain understudied. First, it has been shown that the environment-migration association can be sensitive to the scale of analysis (Hunter et al., 2013; Maclaurin et al., 2015). While recent research on Mexico's U.S.-bound migration was found to be related to rainfall deficits (Hunter et al., 2013) this relationship has oftentimes been investigated at coarse spatial scales (e.g., state) and seems to be highly situated and contingent on particular environmental and social conditions including migration histories (Hunter et al., 2013; Nawrotzki et al., 2013 and 2015b). Coarse-scale analysis may mask within-unit variation of relevant information that could help better understand the role of environmental measures for migration (Maclaurin et al. 2015). Only few studies on migration-environment relationships in Mexico have used spatial scales beyond states (e.g., Nawrotzki and Dewaard, 2016; Nawrotzki et al., 2015a), most of which have used subsamples of municipal units and employed spatially-interpolated (using Kriging, a geostatistical method that creates an estimated spatial surface of values based on a scattered set of measured points) data based on weather station measurements (for an exception, see Barrios Puente et al., 2016, who studied return/circular international migration in 2000–2005).

Furthermore, despite the important internal (or domestic) and international migratory traditions out of rural Mexico, little research has contrasted international and internal migration flows as related to environmental factors and the potential for intensified drought conditions. Because of the political interest in Mexican migration to the U.S. (Kaenzig and Piguet, 2014) prior work has exclusively focused on the relationship between climate and international migration. This unitary focus is unfortunate given that much stronger relationships can be expected for internal migration (Findlay, 2011), which at the very least can provide an important counterfactual to the study of the environment-international migration nexus. This gap in understanding has important implications as there may be interrelationships between these two forms of migration (see King and Skeldon, 2010). Finally, most recent research on Mexican migration-environment associations has focused on time periods prior to 2005. Since then important political changes have resulted in shifts in migratory regimes and it remains an open question if weather patterns influence migration the same way under these changed regimes.

[1]Exacerbating the issue is the unabated emission of carbon dioxide, which is expected to increase the effects of climate change, extending them farther into the future (Parry, 2007).

In this paper, we study the association between municipal-level migration in 2005–2010 and rainfall changes in rural Mexico. We extend prior studies on the topic by studying both internal and international movement and their relationships to rainfall estimates derived from satellite imagery from NASA's Tropical Measurement Mission at the same fine-grained scale. Before presenting our results, we briefly review relevant literature on the topic, describe our data and the methodology used.

2 Background

To date, there is not a migration theory that fully and explicitly incorporates the response of individuals and households to extreme weather events (Hunter, 2005; Gemenne, 2011) though this is an area of evolving scholarship (see review by Hunter, Luna and Norton, 2015). Yet Black et al.'s (2011a) explication of a migration-environment conceptual framework usefully includes micro-level, meso-level, and macro-level interactions between historical, political, and socio-economic characteristics and contexts. Also incorporated is consideration of longer-term environmental strain as contrasted with acute and sudden disasters. We draw from this framework as well as literatures on rural livelihoods (Scoones, 1998), social capital theory (Portes, 1998), vulnerability and adaptation to climate change (Adger, 2006), and the New Economics of Labor Migration (Stark and Bloom, 1985) to conceptually ground our analysis of international and internal migration from and within Mexicoin relation to changes in climate patterns. Analyzing such relationships requires the ability to study the population and environmental characteristics at sufficiently fine analytical spatial scales and in locational correspondence to account for their inherent variability, which often includes aggregating the data to a common administrative unit (e.g., Barrios Puente et al., 2016).

Rural livelihoods in Mexico are deeply contingent on different forms of human, financial, social, and – in particular – natural capital (Scoones, 1998). Environmental stress can impact natural capital and rural livelihoods through both slow (e.g., sea level rise) and sudden onset (e.g., floods, storms) weather events and the response of households and communities to either type of weather event is shaped by structural conditions and social, economic, and demographic factors (Raleigh et al., 2008; Black et al., 2011b). In particular, the vulnerability of socioecological systems (SES) to environmental stress depends on the degree of exposure (e.g., the intensity, frequency, and duration of negative weather events) and socially-explicit modulating factors which mediate the impact of exposure (Adger, 2006). For example, communities may be differentially impacted by the same amount of environmental stress according to their degree of sensitivity. In terms of droughts, this includes an SES's level of agriculture dependency, pre-drought water table levels, as well as available irrigation infrastructure. In addition, vulnerability is contingent on adaptive capacity (Adger, 2006). Household and community adaptive capacity is determined by entitlements not only from the individual financial and human capital but also from the actual and potential resources available from access to market or institutional aid mechanisms (e.g., capital or insurance markets, government programs) coupled with more or less stable networks of exchange and reciprocity (e.g., Goldman and Riosmena, 2013).

Migration can be considered an adaptive strategy (McLeman, 2013) although it is often seen as a last-resort coping mechanism associated with a lack of *in situ* adaptive capacity (e.g., McLeman and Smit, 2006). Somewhat consistent with this idea, the New Economics of Labor Migration framework (Stark and Bloom, 1985) posits that migration is a response to inexistent, inefficient, or malfunctioning credit/capital or crop insurance markets and institutional mechanisms, thus suggesting that mobility is an *ex situ* form of adaptation stemming from a lack of local capacity.

Specific to the migration-environment literature, several key findings are emerging from the burgeoning number of case studies across the globe (Hunter, Luna and Norton, 2015). Overall prior research suggests that the migration-environment association is shaped by interaction between environmental and other macro-level migration determinants. Such determinants include historical-political contexts and policies at both national and international scales. Examples include land tenure policies in Guatemala as a key driver of out-migration from rural areas (Lopez-Carr, 2012) and the colonial history of Niger shaping cropping patterns and the establishment of circular migration streams (Afifi, 2011). In Mexico studies suggest that the climate-migration association may vary with the urbanization level of a community (Feng and Oppenheimer, 2012; Nawrotzki et al., 2015a).

Of course, migration as related to environmental conditions is also impacted by micro factors such as household and individual characteristics. For example, land-poor households in Ecuador were most likely to migrate in response to rainfall variability (Gray and Bilsborrow, 2013), while intense poverty may lessen household ability to migrate in the face of disaster as demonstrated during floods in Bangladesh (Gray and Mueller, 2012). As emphasized in migration theory (e.g., Massey and Espinosa, 1997), social networks also play an important role in perpetuating migration flows by facilitating the provision of housing, employment and other support in destinations. It has been hypothesized that transnational migrant networks may operate as “migrant corridors” (Bardsley and Hugo, 2010), and studies in Mexico support the importance of social networks for the climate-migration association (Hunter et al., 2013; Nawrotzki et al., 2015b).

However, with a few exceptions (e.g., Henry et al., 2004), most of the research on migration-environment linkages has not fully integrated, conceptualized or tested the conditions that favor internal vs. international movement (for a conceptual exposition see King and Skeldon, 2010). Such is a key contribution of the work presented here and Mexico represents a particularly relevant case given the nation's large and sustained tradition of both international and internal migration from rural areas (cf. Garza, 2003).[2] Climatologically, Mexico is also likely to be particularly sensitive to impacts associated with climate change, attributable to the large changes expected in sub-tropical areas (Boyd and Ibarrarán, 2009; Magrin et al., 2014). There is growing evidence that the country may already be experiencing some effects of climate change, including sea level rise and changes in precipitation patterns (Hopp and Foley, 2003; Burke and Maidens, 2004; Lesser, 2007; Sachs and Redlener, 2010). Hernandez

[2]For instance, between 2005 and 2010, 1.1 million Mexicans emigrated internationally. Although this number is large, it represents a slowdown relative to the 1995–2000 census window, during which approximately 1.6 million migrants were identified as migrating internationally. On the other hand, internal migration has seen a rise over the same time interval, increasing from 5.8 million recorded migrants between 1995 and 2000 to 6.3 million in 2005–2010.

et al. (2003) suggest that further increases in carbon emissions could cause up to 39 percent of the Mexican territory to be under persistent drought conditions. Some climate scenarios project that areas in southern Mexico will effectively become unsuitable for rain-fed agriculture (Adamo and de Sherbinin, 2011).

Environmental stress for Mexican residents – especially in poor rural households – has become increasingly evident (Eakin, 2005; Gay et al., 2006; Eakin and Wehbe, 2009). With only 23% of cropped land irrigated in 2001 (Carr et al., 2009), many rural farmers in Mexico are strongly dependent on rainfall and thus are highly vulnerable to shifts in climatologic patterns. These households and communities have also had traditionally low adaptive capacity given their chronic underdevelopment, a situation that has generally worsened in recent years with agricultural commodity market liberalization (Eakin, 2005; Zepeda, et al. 2009).

As outlined above, some research has examined the conditions under which U.S.-bound migration from Mexico is a likely response to weather events and, more broadly, a changing climate. However, these studies employ spatially aggregated (i.e., within the boundaries of the administrative units used) data as a way to incorporate environmental measures, socio-economic and migration data in spatial correspondence thus being able to evaluate their variability across the study area. This often comes at the cost of loosing the individual or household level in the analysis (e.g., Barrios Puente et al., 2016) but allows to explore this relationship at the community/municipality level, which is often the unit of analysis most relevant for policy making.

A number of gaps in prior research on Mexican climate-related migration can be identified: (1) While a growing number of studies has investigated the relationship between climate factors and international migration (e.g., Feng and Oppenheimer, 2012; Hunter et al. 2013; Nawrotzki et al. 2015b), or focused on the role of natural disasters for migration in general (Saldaña-Zorrilla and Sandberg, 2009), we know very little about the relationship between internal migration and climate factors. While scholars often assume that climate-related migration will mostly be short distance and internal (Findlay, 2011), international climate migration is possible in the presence of strong social networks (Bardsley and Hugo, 2010), and it is unclear whether in the Mexican case internal migration is similarly influenced by climate factors as international migration. (2) While some recent research has employed municipality-level climate data (Nawrotzki et al. 2015a–c; Nawrotzki and DeWaard 2016), these studies focus on a small selection of municipalities and lack generalizability at the national scale. In contrast, studies employing representative census data usually measure climate impacts at a very coarse state-level (e.g., Feng and Oppenheimer, 2012; Nawrotzki et al., 2013) which may hide important variation relevant to the process of interest.(3) While this earlier work has focused predominantly on the migration around the year 2000 (e.g., Barrios Puente et al., 2016), no study to date has investigated the climate-migration association in Mexico for more recent years. (4) There is some evidence that the climate-migration association is mediated through employment in the agricultural sector (Mueller et al., 2014; Nawrotzki et al., 2015a). However, we know little about how the climate-migration relationship varies with availability of specific features (e.g., irrigation capacity) critical for local agricultural production. The present study is an attempt to begin filling these gaps. We employ municipality-level migration data from the complete 2010 census in combination with high-resolution rainfall data to investigate whether rainfall decline differentially influences internal versus international migration.

3 Data and Methods

3.1 Data

The analyses integrate data from 2,455 Mexican municipalities, a spatial scale roughly analogous to U.S. counties (see Figures 1 and 2). Data sources are summarized in Table 1 and individual variables are described in Table 2 (summary statistics of relevant control variables are available upon request from the corresponding author). Our two main indicators of internal (i.e., inter-municipal) and international migration for each municipality of origin between 2005 and 2010 were calculated using a 10% extract from the Integrated Public Use Microdata Series (IPUMS) made available by the Minnesota Population Center (2011) from the original long form sample data collected by the Mexican National Institute of Statistics and Geography (INEGI) (Table 1). The migration counts were summarized to compile municipality-level migration outcome variables. From this extract, we also calculated basic municipality-level sociodemographic information (summary statistics) such as age (AGE), employment status and income (INCOME) (Table 2). We calculated the proportion of internal migrants from each municipality a decade earlier using the 2000 census data as a measure of internal migrant networks (HIST_MIG). In addition, we obtained both data on remittances received (REMIT, as a proxy for the intensity of migrant networks) and official population estimates derived from the 2005 Population Count data from INEGI. The 2005 Population Count is a mid-decade census-like enumeration, which we use as an offset (i.e., estimates of exposure to the risk of emigrating) in our Poisson models, as explained below.

Places more dependent on agriculture, particularly those without irrigation systems (i.e., more dependent on rainfall) are likely more sensitive to climate variability. To examine this relationship, we use information on crop output (TOTALAGSURFACE) and the amount of this output produced in rainfed lands (IRRIG) in each municipality using data from the Mexican Agricultural Census (2007), also carried out by INEGI (Table 2). In line with prior work, we construct a measure of precipitation relative to long-term conditions as a proxy for levels of climatic variability. First, we obtained short-term (2005–2009) rainfall averages (RAINFALL) within municipalities using the Tropical Rainfall Measuring Mission (TRMM) satellite observations. These short-term municipality-level rainfall measures will be employed to control for absolute precipitation in the models and are used to estimate rainfall deviations from long term records as described below. The TRMM data retrieved were processed by the NASA Goddard Space Flight Center using version 7 of algorithm 3B42 (see http://trmm.gsfc.nasa.gov/3b42.html), which translates High Quality Microwave Estimates (HQ) and Infrared estimates from the National Climatic Data Center (NCDC) and Climate Prediction Center (CPC) into estimates of 3-hourly precipitation.[3]

[3]The quality of HQ is known to vary over time as additional data sources have been introduced, leading to inaccuracies over small time steps much smaller than those used in this paper (e.g., even at the monthly scale these are believed to be corrected). Efforts are

Because TRMM's Precipitation Radar has only been online since 1998, we lack data from the same source to estimate our long-term baseline, a limitation that has been reported previously (Barrios Puente et al., 2016). A comparison to a different data product such as WorldClim can be problematic due to differing interpolation techniques used and data quality. For this purpose, we use a classification of dryness-wetness developed by INEGI personnel (based on a modified Koeppen Climate Classification System, the most widely used system for classifying the world's climates based on temperature and precipitation), that allows identification of climate microregions based on dryness and temperature. We use this classification (in Mexico, the five classes are very dry, dry, semi-dry, sub-humid, and semi-humid) to label historical baseline conditions in each municipality. A measure for contemporary dryness in each municipality that can be related to the historical class labels is derived by classifying the TRMM estimates into quintiles. The two classifications were compared to construct a binary indicator (LESS_RAIN) for each municipality indicating whether more or less than expected rainfall has been observed during the 2005–2009 period relative to the historical baseline data. For example, municipalities that fell into a lower quintile of rainfall in the contemporary time period than in the historic time period were coded with a "1", indicating less rainfall received than historically typical.

3.2 Methods

To assess the influence of changes in precipitation on migration, we make use of the sustainable livelihoods (Scoones, 1998; Carney and Britain, 2003) and vulnerability frameworks to aid in the identification of five types of independent variables representing human, physical, financial, social, and natural capital (see Table 2). Guided by this framework, we broadly follow a two-step procedure:

1. We aggregate remotely sensed weather (0.25 degree raster data), IPUMS (individual-level microdata), and other tabular ancilliary (i.e., agricultural census information) data to the municipality scale, to reflect summaries of the different capitals (Section 3.2.1);
2. Stratified (i.e., differentiated by reliance on rainfed agriculture) Poisson models of outmigration are fit to the municipality-scale data (Section 3.2.2).

3.2.1. Aggregation of Data—The aggregation of social and biophysical data to the municipality scale is done using two different approaches, one for tabular data (IPUMS) and one for spatial gridded data (TRMM precipitation data). In the case of IPUMS-sourced tabular data, using the 10% sample of individual-level information, migratory and sociodemographic characteristics for the whole population in a municipality were estimated by calculating weighted sums and averages, respectively. Sample weights for each person (and household) were provided by IPUMS, indicating the expected number of persons with these demographic characteristics residing in the respective municipality. These sample weights are used to derive a representative characterization of the total population of a given municipality.

underway to replace the 3B42 algorithm with an updated approach – the Global Precipitation Measurement IMERG algorithm (see Huffman, 2012).

Migration data were collected retrospectively (i.e., at the destination) with the Census questionnaire providing information on the municipality of residence five years prior to the interview. A different item in the questionnaire indicated if any household members had migrated internationally during the same time window. Thus internal outmigration (DOM_MIG) was estimated for the municipality of origin (five years prior). In contrast, international outmigration between 2005 and 2010 was estimated for the municipality in which the interview took place in 2010 (INT_MIG). Based on these assumptions about the location and formation/dissolution of households during the 5-year window, and given our interest in analyzing both internal and international movement, we aggregated both types of migration estimates (independently) to the municipality level. Because the exact year of a internal or international move within the 5-year observation window (2005–2010) is unknown, we employ socioeconomic controls based on information from the 2010 census as a reasonable approximation for the local context in which migration occurred.

These municipality-level estimates were joined to a spatial data layer delineating 2010 municipalities obtained from INEGI. Both historical climate classification and agricultural census information were provided by INEGI at the municipality scale, and thus required no aggregation. The TRMM short-term precipitation data were aggregated to the municipality scale following the piecewise approximation procedure for areal interpolation detailed in Goodchild et al. (1993):

$$V_t = \sum_{s=1}^{S} U_s \left(\frac{a_{\mathrm{st}}}{\sum_{t=1}^{T} a_{\mathrm{st}}} \right) \quad \text{(eq. 1)}$$

where t is an identifier for the zone one is aggregating or interpolating to (the municipality or our *target* zone), s is an identifier for the zone one is aggregating from (i.e., a TRMM pixel or *source* zone), T and S represent the total of all zones t and s, U_s represents the value of interest at source zone s (in our case, precipitation measured in mm/hour), a_{st} is the area of overlap between the two zones, and V_t is the estimated value for the target zone. In our application, this procedure reapportions each pixel of the TRMM dataset according to its overlap with each municipality – TRMM pixels that fall entirely inside of a municipality will have their precipitation value utilized with full weight when calculating the overall average, while those that fall on the border will be assigned a smaller weight according to the area of overlap. The resulting weighted precipitation averages are joined to the municipality layer.

3.2.2 Modeling and Stratification—We use Poisson regression models to examine the influence of changes in precipitation on both international and internal out-migration between 2005 and 2010. The models take the general form:

$$\log(y_i) = P + \beta_0 + x_n \beta \quad \text{(eq. 2)}$$

where y is the count of migrants (either internal or international) that left municipality i between 2005 and 2010. Given that differences in the number of migrants could be a simple reflection of place size, each model is fit with an offset term, P, also known as exposure, in our case the municipality's total population in 2005. By constraining the coefficient of P to an implicit value of 1, we effectively model the rate of out-migration as opposed to migration flows, a desirable property of the model given our interest in modeling migration risks. Finally, β_0 is the constant (i.e., the mean municipality migration rate with all covariates equal to zero), while β denotes a vector of k coefficients, one for each independent variable.

Two separate models were fit, one for international and one for internal migration (see Table 2). In addition, since past research suggests that migration processes unfold differently as a function of the overall level of agricultural dependence on weather, each model was run for two groups (or strata) according to the estimated degree of sensitivity of municipalities to environmental stress associated with rainfall deficits expressed by the percentage of rainfed crops (IRRIG). As opposed to using interactions, this allows coefficients of all predictors to vary with changing rainfall sensitivity. To investigate how the described explanatory and control variables are associated with outmigration under conditions of more direct, higher level dependence on rainfall for agriculture, in our first set of models we included only municipalities where more than 50% of crops are rainfed. In contrast, a second set of models were fit in which only municipalities less directly reliant on rainfall (defined as those at or below the 50% threshold) are included.[4] This stratification is believed to be critical for the understanding of drivers of outmigration and will help to fill important knowledge gaps with regards to historical dependencies on rainfall in the agricultural sector.

As mentioned, separate models were fit for internal and international migration, for a total of four models – two for municipalities with a low reliance on rainfed agriculture, and two for municipalities with a high reliance on rainfed agriculture. Final model selection was conducted using an iterative, deductive process in which a variety of factors including model fit, variable significance, and statistical assumptions were considered. During the modeling process, two measures of human capital (the percent of disabled individuals and the percent of females) were omitted in both models due to multicollinearity.

4 Results

The results are presented by stratum with a focus first on municipalities with high levels of rainfed agriculture. Within each stratum, we first present results for international migration which are then contrasted with results for internal migration. Subsequently, we report some critical observations made for the control variables differentiated for the models of international and internal migration and finally summarize central key findings contrasting international and internal migration as associated with rainfall variability.

[4]Because this 50% threshold is somewhat arbitrary, we tested the robustness of our model by systematically altering the threshold to 60, 70, 80 and 90 percent. Regardless of the threshold chosen, the directionality of our variable of interest (LESS_RAIN) remained the same as described in the results.

4.1 Stratum of Rainfall-Reliant Municipalities (>50% Rainfed Agricultural Production)

The results of the analysis are presented in Table 3. Goodness of fit (pseudo r^2) for the model explaining **international migration** in rainfall-reliant municipalities is 0.51. All variables are significant ($p < .05$). In municipalities highly reliant on rainfall for agricultural purposes (>50% rainfed), more rainfall is associated with less international migration, suggesting that in periods of potentially higher agricultural productivity, the necessity of international migration for livelihood security may be lessened.

With regard to control variables, international migration has a negative relationship with income in rainfall reliant areas – municipalities with higher levels of household income tend to be involved at lower levels in international migration. There is a positive relationship between remittances and international outmigration, and a negative relationship between the historic number of internal migrants (1995-200) and contemporary (2005–2010) international migration suggesting that internal and international migration may represent substitute streams. In highly rainfall-dependent municipalities, an older average age is related to a reduced proportion of international migrants, suggesting a more stable population perhaps beyond prime-age years of more costly international migration. Further, municipalities with greater agricultural area experienced lower levels of migration in rainfall-dependent municipalities.

For **internal migration**, the goodness of fit (pseudo r^2) for our model examining rainfall-reliant municipalities is 0.33, less than that for international migration although all variables are significant. In municipalities highly reliant on rainfall for agricultural purposes (>50% rainfed), additional rainfall is associated with fewer internal migrants. Like international migration (though with a smaller negative coefficient), this suggests that in periods of potentially higher agricultural yield, the need for migration as a strategy for livelihood security may be lessened.

In municipalities with high levels of rainfall reliance there is a negative relationship between internal migration and remittances, potentially resulting from a substitution effect with international migration which showed a positive relationship. Historic internal migration (1995 – 2000) had a positive correlation with internal migration during the study period (2005–2010) likely reflecting the importance of past social networks in facilitating and supporting migration streams. As opposed to international migration, municipalities with higher average age experienced proportionally more internal migration, possibly reflecting the fact that people of older ages participate in internal migration than in international streams within municipalities more reliant on rainfed agriculture.

4.2 Stratum of Low Rain Reliance Municipalities (<50% Rainfed Agricultural Production)

Turning to municipalities with lower levels of dependence on rainfed agriculture, in the model for **international migration**, the goodness of fit (pseudo r^2) is 0.65 and all variables are significant (alpha = .05). In all, higher levels of rainfall are associated with higher levels of international migration, suggesting that perhaps times of high livelihood security actually allow for the investment in relatively more expensive forms of mobility in these municipalities that are supposedly more stable with regards to agricultural production.

International migration retains a negative relationship with income, a positive relationship between remittances and outmigration, and a negative relationship between the historic number of internal migrants (1995-200) and contemporary (2005–2010) international migration. In low rainfall reliance municipalities an older average age tended to be associated with higher proportions of international migrants, as is higher proportions of agricultural area.

For the model examining **internal migration** in low rainfall reliance municipalities, goodness of fit (pseudo r^2) was 0.33. All variables – except agricultural surface size - are significant (alpha = .05). In low rain reliance municipalities (<50% rainfed), similar to international migration, higher levels of rainfall are associated with higher levels of internal migration.

In areas with low reliance on rainfed agriculture, internal migration exhibits a negative relationship with remittances. Historic internal migration (1995 – 2000) retained a positive correlation with internal migration during the study period (2005–2010) and higher average age was associated with lower proportions of internal migrants.

4.3 International Migration: Control Variables

The results from the model for international outmigration are mediated by the unique migratory situation in Mexico, which is partially reflected through the use of control variables. With nearly a hundred years of history of migration to the United States, social networks are critical for individuals seeking to use migration as an adaptive strategy. This is represented in our models as captured by the percentage of households in a given municipality receiving remittances (REMIT), making the assumption that a larger number of individuals receiving remittances is associated with access to stronger migration networks. This work provides further evidence for the theory and findings of Nawrotzki et al. (2013) and Hunter et al. (2013), which suggest a linkage between a higher level of received remittances and higher levels of migration. REMIT's coefficient was both significant and showed the same direction irrespective of the rain fed threshold chosen for stratification (see Table 3, panel A).

Also interesting with regard to international migration is the change in direction for the AGE coefficient between strata. For municipalities with low rain reliance, AGE had a small but positive and significant coefficient, whereas for municipalities with more than 50% rainfed crops AGE was negative. This could be indicative of the mobility of each population: Higher proportions of people who are working at or own farms with extensive irrigation may have access to funds and social networks allowing international migration later in life than for those that work at or own mainly rain-fed farms. It could also indicate a preference of age groups for certain types of migration showing a shift between the two strata.

4.4 Internal Migration: Control Variables

In the case of internal migration, the relationship between income and migration was positive, as expected, in both strata. While the REMIT variable is negative for internal migration, this does not indicate that social networks are less important. Rather, internal networks may be captured by the number of migrants a municipality sent to other internal destinations between 1995 and 2000 (HIST_MIG). For all thresholds used to define the rain-reliance strata (between the initial 50% and 90% rainfed crops) HIST_MIG's coefficient remains both positive and large. This suggests that internal social networks are key in determining migratory strategies in both strata.

Internally, AGE has a positive coefficient in rainfall dependent areas and a negative coefficient in areas with low rain reliance – the inverse relationship seen for international migration. This could be indicative of broad preferences of age groups for different types of migration – in this case elderly populations choosing internal over international migration in rain-reliant municipalities and the opposite in less rain-reliant communities.

4.5 Key Findings: Comparing International and Internal Migration as associated with Rainfall

This study has a particular focus on the three terms to capture the association between rainfall and migration: LESS_RAIN, RAINFALL, and an interaction term between these two. LESS_RAIN, a binary value in which a one indicates the municipality received less rainfall than usual, always had a positive relationship with migration. This suggests that, for both internal and international migration, municipalities that received less rainfall than usual also sent more migrants than usual. This is a particular key finding confirmed by our robustness tests (see footnotes 4 and 5) which demonstrate that this relationship holds, independent on the percentage of rain-fed land used to define rain-dependent municipalities.

RAINFALL and the interaction term with LESS_RAIN (LESS_RAIN*RAINFALL) both help to capture the absolute impact of additional rainfall on migration. In both the international and internal case, highly rain-reliant municipalities always exhibited a negative relationship between precipitation (RAINFALL) and outmigration: If it rained more in rain-fed areas, fewer migrants left. In municipalities that are well irrigated the relationship between migration, both international and internal, and RAINFALL is positive (Table 3). For international migration, this relationship warrants further study as it seems to be interrelated with amenity-migratory decisions, natural disasters, and/or changing economic structure. Internally, we see a positive relationship with a small coefficient, but municipalities where less rainfall than usual was received ultimately have a negative relationship due to the incorporation of the interaction term.

5 Conclusion and Discussion

In this study we have investigated the relationship between rainfall decline and internal and international migration. In line with much prior work we observe that a decline in rainfall is associated with an increase in migration (Barrios Puente et al., 2016; Hunter et al., 2013; Nawrotzki et al., 2015b). The present study contributes to the examination of the relationship between migration and environmental factors in at least three key ways: First,

[5]A spatial lag model was calculated with the data to test for potential spatial spillover effects, and if the inclusion of spatial factors would alter our findings. In this test, it was found that units of observation with high levels of migration surrounding it tended to also have high levels of migration, but that additional rainfall still contributed to a reduction in out migration.

we illustrate that the migration-climate patterns observed at coarse scales (e.g., state-level: Feng and Oppenheimer, 2012; Nawrotzki et al., 2013) or at finer scales but limited scopes (e.g., based on a subsample of rural municipalities: Hunter et al., 2013; Nawrotzki et al., 2015b) hold for the case of international migration when examined across a full set of Mexican municipalities. This is important as it provides further evidence that the socio-economic and environmental mechanisms that drive international migration do not operate only via broad scale (e.g., state-level) shifts in economic policy in response to environmental changes, but also at more local scales. In other words, our observations provide evidence that these findings are robust to scale and this indicates some potential for more general validity in similar settings where no fine-scale data is available. Second, we examine a unique time in Mexico's history in which differing political regimes (both in the U.S. and Mexico) resulted in dramatically different migratory regimes (Massey et al. 2016). That changing weather patterns can be observed to influence migration in similar ways across both the historic and contemporary record in Mexico results in a higher degree of confidence in these relationships, and that the mechanisms that relate weather to migration are resilient to even broad-scope political change. Third, as a new insight, we find evidence that changes in precipitation can also drive internal migratory patterns in Mexico - potentially stronger than international migration, which is in line with research from the African continent (Henry et al., 2004) and theoretical considerations (Findlay, 2011). Henry et al. (2004) differentiated migration by destination and duration in Burkina Faso and found that short-term rainfall deficits tend to increase long-term migration to rural areas (internally), similar to what has been reported in this study, but decrease short-term moves to distant destinations (abroad) which contradicts our observations for international outmigration from Mexico, likely due to a higher financial burden for international migration from Burkina Faso. While the strong signal for internal migration could be due to a variety of factors (e.g., increased costs of international migration as compared to internal; the unique political situation of Mexico and border laws with the U.S.; spatial variation in migratory patterns not examined in this article), the finding suggests a need for further research on internal, sub-national migration alongside research focused on international migration in Mexico as well as the interactions between the two migration forms (Lindstrom and Lauster, 2001). Of course, it is important to understand that the relationship between rainfall change and outmigration is bound by thresholds (Bardsley and Hugo, 2010) i.e., exceptionally little (droughts) as well as excessive rainfall (leading to flooding) will adversely influence livelihoods and often induce outmigration.

Although carefully conducted, this study is not without limitations: First and foremost, we elect to use the TRMM dataset to measure recent rainfall due to the relatively fine spatial resolution and density of systematically-produced observations. However, the temporal limitations of this data prevented a long-term systematically collected precipitation record. While we considered many alternative data products (i.e., WorldClim, UDEL), ultimately we opted to use the fairly conservative Köppen-based classification system in combination with the TRMM rainfall data since 1998. We will investigate the robustness of our findings to alternative approaches as one focus of ongoing research.

Second, the census information used in this study does not capture instances of (a) entire households that migrated internationally (as these individuals would not be captured by the question of how many members of a household have migrated internationally in the last five years), or (b) undocumented migration (in this case, migration not captured by the census). By contrasting the migration flows examined in this study to surveys in which substantially more detailed– but limited in spatial scope - information on international outflows are available (i.e., the Mexican Migration Project), future research will shed light on the uncertainties introduced by the limitation of the census data.

Third, we would like to highlight the potential for bias due to unobserved characteristics in the final models, including spatial relationships between administrative units (e.g., spatial lags) as well as omitted variables important to the relationship of interest. While we have attempted to mitigate these concerns through careful variable selection (including the testing of many variables such as urban travel times not included in the final model) and robustness tests[5], traditional Poisson-adjusted modeling approaches still carry a potential for bias due to certain assumptions made. The authors are currently exploring approaches to overcome many of these concerns[6], explicitly by incorporating propensity score matching with spatial statistical approaches.

With these limitations in mind, our study has important policy implications: We find that a decline in rainfall and droughts can lead to elevated migration rates. Migration can be seen as a form of livelihood diversification used by populations to adapt to climate change (Black et al., 2011a). As such, programs and policies may facilitate migration with the goal to improve livelihood resilience among households in climate change-affected communities. However, migration, especially when crossing international borders, is often a less desired outcome (Kaenzig and Piguet, 2014) and in situ livelihood based climate adaptation assistance may be a preferred solution. We observe strongest migration responses to rainfall deficits in regions with little irrigation infrastructure. As such, livelihood based programs for climate change adaptation may be best targeted towards communities heavily dependent on seasonal rainfalls. To reduce dependence on natural rainfall, programs may help funding small scale irrigation systems (Burney et al., 2013) or the development of seasonal climate forecast and monitoring systems (Cooper et al., 2008). Such programs may serve the dual benefit of improving livelihoods of climate impacted communities and reducing the need to engage in international and internal relocation that may pose problems for governing authorities.

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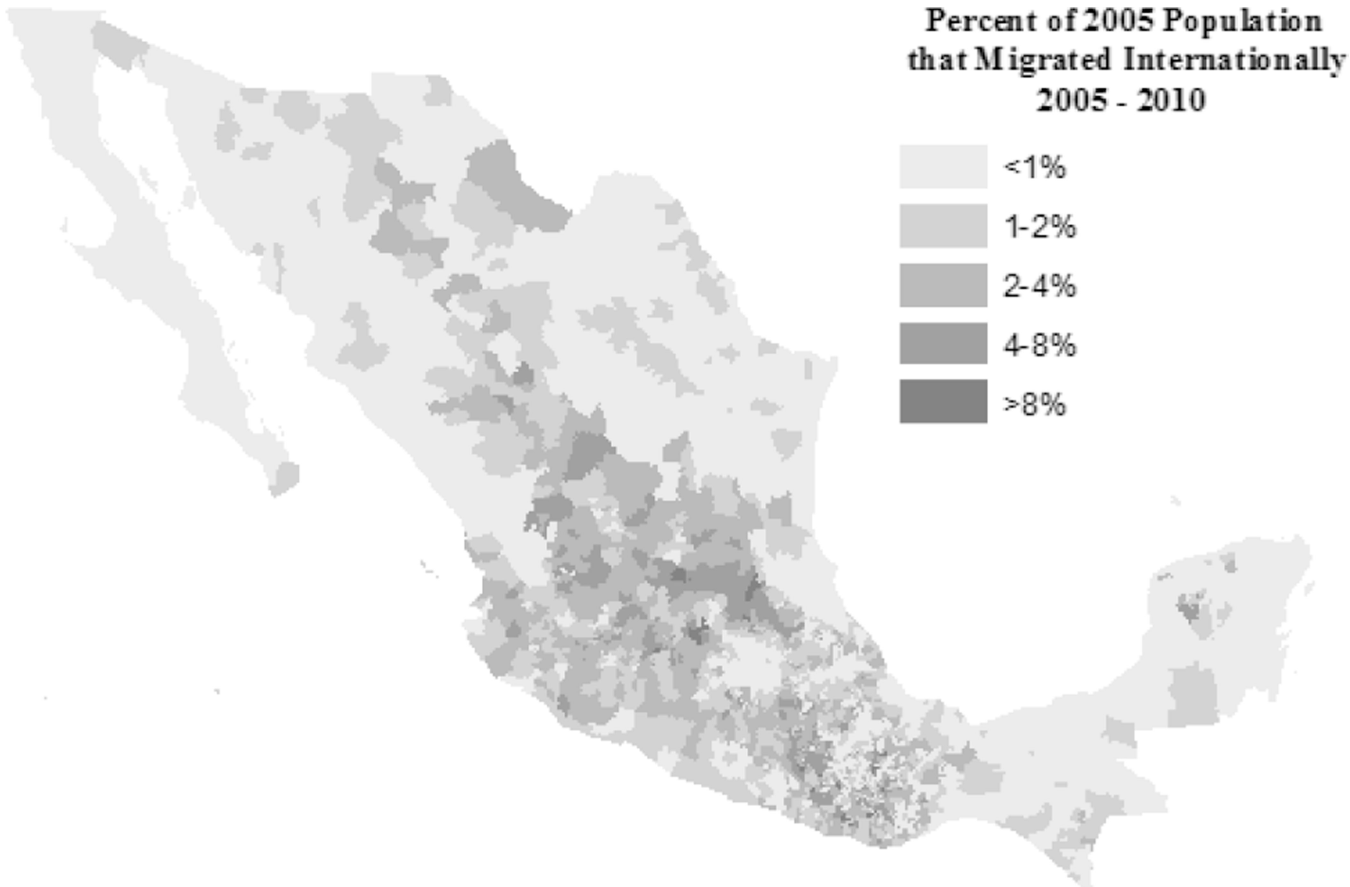

Figure 1.
Municipal international migration rate in 2005–2010

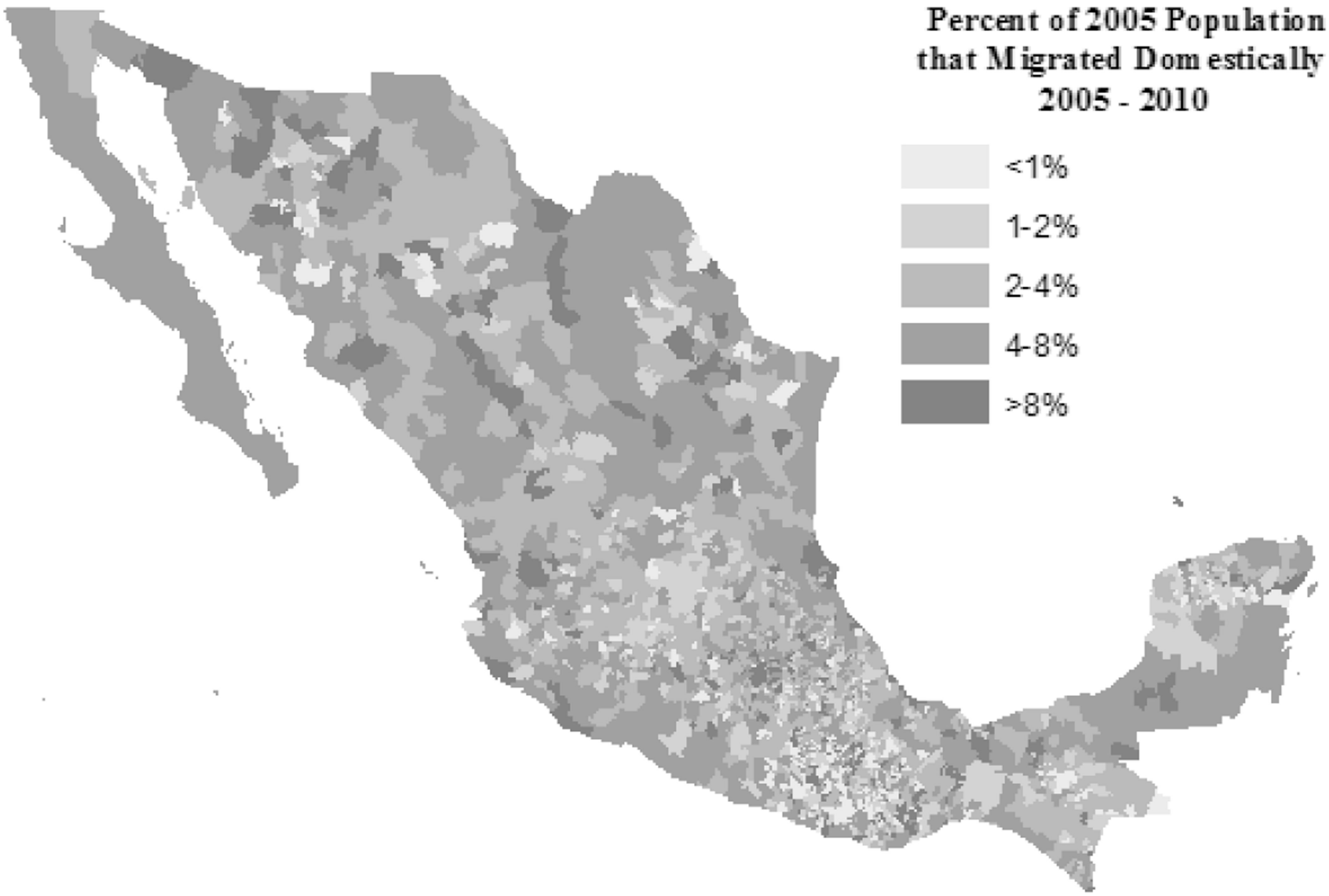

Figure 2.
Municipal internal migration rate in 2005–2010

Table 1

Data sources used in the analysis.

Dataset	Description	Source
Integrated Public Use Microdata Series (IPUMS)	Internationally harmonized micro-census data. Includes sociodemographic, migration, household, and geographic information in Mexico.	Preprocessed data was retrieved from the Minnesota Population Center (2011). Original data from National Institute of Statistics and Geography, Mexico
Tropical Rainfall Measuring Mission (TRMM)	High resolution (0.25 degr.), satellite-derived estimates of precipitation available since circa 1998.	(NASA-JAXA, 2013)
Remittance Data	Provides information on the percent of households receiving remittances within each municipality.	2000 Census (INEGI)
Koeppen Classifications	Long-term climate classifications for different biomes across Mexico	INEGI

Table 2

Response and explanatory variables used in this analysis. Under "Expected Sign" we indicate for international and internal migration the expected sign of the regression coefficients for the explanatory variables; +/− means that it is not clear, based on prior research, which sign to expect.

Variable			Description	Source	Expected Sign: INT	Expected Sign: DOM
Response variables	**Out-Migration**	INT_MIG	Proportion of the population that migrated out of a municipality to an international destination, 2005–2010.	IPUMS	N/A	N/A
		DOM_MIG	Proportion of the population that migrated out of a municipality to an internal destination, 2005–2010.	IPUMS	N/A	N/A
Explanatory variables	**Physical Capital**	IRRIG	% of Crop Units Irrigated within a Municipality	INEGI	+	+
	Financial Capital	INCOME	The average peso's earned by households within a municipality, 2010.	IPUMS	+	+
	Human Capital	DISAB	Proportion of individuals within the municipality who are disabled, 2010.	IPUMS	−	−
		AGE	Average age of individuals within the municipality, 2010.	IPUMS	−	−
		SEX	Proportion of individuals within the municipality who are female, 2010.	IPUMS	+	+
	Social Capital	REMIT	The proportion of households within a municipality that received at least some remittances (2000).	INEGI	+/−	+/−
		HIST_MIG	The proportion of the population that migrated internally from a municipality from 1995 to 2000.	IPUMS	+/−	+/−
	Natural Capital	RAINFALL	The amount of rainfall (in average mm / hour) each municipality received from 2005 to 2009.	TRMM	−	−
		LESS_RAIN	A binary 1 or 0, in which a 1 indicates the region received more rainfall than was historically usual.	TRMM / INEGI	−	−
		TOTALAGSURFACE	The total surface area (Hectacres) of agricultural land within each municipality (2007).	INEGI	+/−	+/−

Table 3

Poisson regression coefficients modeling municipal rate of international and internal migration in 2005–2010 according to the level of rainfall reliance in the municipality.

	(A) International migration		(B) Internalmigration	
	Higher Rain Reliance (>50% rain fed)	**Low Rain Reliance (≤50% rain fed)**	**Higher Rain Reliance (>50% rain fed)**	**Low Rain Reliance (≤50% rain fed)**
RAINFALL 2005–2009 rainfall (avg. mm/hr)	−0.53 *	7.7 *	−1.9 *	0.48 *
LESS_RAINFALL Municipality received less rainfall than historically usual	0.28 *	0.065 *	0.02 *	0.23 *
LESS_RAINFALL×RAINFALL 2005–2009 rainfall · more rainfall than historically usual	−0.811 *	−2.1 *	−0.398 *	−2.7 *
TOTALAGSURFACE Total agricultural surface in municipality (ha)	−0.00000062 *	7.58E-08 *	−0.000003 *	−0.000002
REMIT Percent of households in municipality receiving remittances from abroad 2000	0.054 *	0.065 *	−0.02 *	−0.03 *
HIST_MIG Percent of households with at least one internal, inter-municipal migrant, 1995–2000	−5.04 *	−6.98 *	4.98 *	4.06 *
INCOME Average income in municipality, 2010	−0.0002 *	−0.00009 *	0.0001 *	0.0001 *
AGE Average age in municipality, 2010	−0.012 *	0.02035 *	0.05 *	−0.04 *
Constant	−3.8	−5.23	−4.5	−2.16
N	2092	242	2121	247
Pseudo R^2	0.51	0.65	0.54	0.33

* denotes statistical significance at the .05 level.