

Climate shocks and rural-urban migration in Mexico: exploring nonlinearities and thresholds

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Abstract Adverse climatic conditions may differentially drive human migration patterns between rural and urban areas, with implications for changes in population composition and density, access to infrastructure and resources, and the delivery of essential goods and services. However, there is little empirical evidence to support this notion. In this study, we investigate the relationship between climate shocks and migration between rural and urban areas within Mexico. We combine individual records from the 2000 and 2010 Mexican censuses ($n = 683,518$) with high-resolution climate data from Terra Populus that are linked to census data at the municipality level ($n = 2321$). We measure climate shocks as monthly deviation from a 30-year (1961–1990) long-term climate normal period, and uncover important nonlinearities using quadratic and cubic specifications. Satellite-based measures of urban extents allow us to classify migrant-sending and migrant-receiving municipalities as rural or urban to

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examine four internal migration patterns: rural-urban, rural-rural, urban-urban, and urban-rural. Among our key findings, results from multilevel models reveal that each additional drought month increases the odds of rural-urban migration by 3.6%. In contrast, the relationship between heat months and rural-urban migration is nonlinear. After a threshold of ~34 heat months is surpassed, the relationship between heat months and rural-urban migration becomes positive and progressively increases in strength. Policy and programmatic interventions may therefore reduce climate induced rural-urban migration in Mexico through rural climate change adaptation initiatives, while also assisting rural migrants in finding employment and housing in urban areas to offset population impacts.

Keywords Environment · Mexico · Climate change · Internal migration · Rural-urban migration

1 Introduction

While interest in climate factors as possible drivers of transnational migration remains (Gray and Wise 2016; Nawrotzki and DeWaard 2016), a small but growing number of quantitative studies have started to examine the relationship between climate shocks and internal migration (Hunter et al. 2015), and for good reason: First, owing to differences in exposure, sensitivity, and adaptive capacity (Adger 2006; IPCC 2014), places and populations within countries differ in their vulnerability to climate shocks, and this heterogeneity deserves to be unpacked. For example, it is well-documented that persons living in rural areas are more susceptible to climate shocks than those living in urban areas given strong dependencies on the agricultural sector for livelihoods and sustenance (Feng and Oppenheimer 2012; Hunter et al. 2015; Scoones 1999).

Second, while most people prefer not to move (Findlay 2011), those that do move typically migrate short distances to minimize the economic and psychosocial costs associated with migration (Bodvarsson and Van den Berg 2009). Internal moves are typically directed to places where migrants can obtain the necessary capital to offset livelihood uncertainties at home via remittances (Stark and Bloom 1985). Importantly, this dynamic is often reflected in rural-urban migration (Barrios et al. 2006; Mberu 2005) because metropolitan areas tend to offer employment in more diverse and less climate-sensitive labor markets, not to mention higher wages. However, because the skills of migrants from rural areas sometimes do not transfer to urban labor markets (Ratha et al. 2011), rural-rural and urban-urban migration (cf., Dillon et al. 2011) might also be common responses to climate shocks given similar livelihood environments in the migrant-sending and migrant-receiving areas.

Finally, the confluence of differential vulnerability to climate shocks and multiple and diverse types of migration patterns between rural and urban areas within countries suggests that the relationship between climate shocks and internal migration is probably not “monolithic and unidirectional” (Gray and Wise 2016, p. 556). Several recent studies have shown that the climate-migration relationship is characterized by important nonlinearities and thresholds (Bardsley and Hugo 2010; Bohra-Mishra et al. 2014; Gray and Wise 2016). Understanding these nonlinearities is important for a timely policy response to major and potentially irreversible shifts in livelihood environments (McLeman et al. 2016).

Given the need to unpack the relationship between climate shocks and internal migration, it is surprising that current research has neglected an important case that is likely ground zero for understanding the climate-migration relationship in North America: Mexico (see supplement S1: Case). This oversight is potentially consequential for several reasons. First, Mexico is

highly vulnerable to climate shocks given the confluence of observed and projected climatic changes (Collins et al. 2013; McSweeney et al. 2008), strong dependencies on the agricultural sector (Conde et al. 2006; Wiggins et al. 2002), and limited technological infrastructure (Winters et al. 2002). Pronounced differences in livelihood environments render rural communities generally more susceptible to climate shocks (Feng and Oppenheimer 2012; Nawrotzki et al. 2015a), but urban areas also face climate-related challenges (Romero-Lankao 2010). Moreover, recent changes in agricultural employment (Charlton and Taylor 2013; Scott 2007) suggest the need for a closer look at climate sensitivity and internal migration in rural Mexican communities.

Second, likely an outgrowth of the large body of research on Mexico-U.S. migration (e.g., Massey 1987; Massey and Espinosa 1997), prior research on the climate-migration relationship in Mexico has focused exclusively on international migration. These studies have documented evidence of a climate signal, with warming temperatures and declines in precipitation contributing to international out-migration (Barrios Puente et al. 2015; Feng and Oppenheimer 2012; Hunter et al. 2013; Nawrotzki et al. 2015b). However, most contemporary migration in Mexico is internal (versus international) (Aguayo-Tellez and Martinez-Navarro 2013; Runfola et al. 2016), and we presently lack comparable information on the relationship between climate shocks and internal mobility in Mexico. These internal migration flows are of particular interest to policy makers and local authorities given the potential impacts on population (e.g., size, density, and composition), infrastructure, and the availability and provision of resources. For example, climate-related increases in rural-urban migration could overwhelm the capacity of metropolitan areas to deliver essential services such as health, sanitation, education, and public safety (Adamo 2010).

Accordingly, this paper breaks new ground by providing the first study of the relationship between climate shocks and four types of internal migration patterns in Mexico: rural-urban, rural-rural, urban-urban, and urban-rural. We ask: (1) *Do climate shocks influence internal migration patterns between rural and urban areas in Mexico?* (2) *If so, are these differences manifested in nonlinearities and thresholds in the observed climate-migration relationships?*

2 Data and methods

We combined data from the 2000 and 2010 Mexican censuses (1% extracts) from IPUMS International (MPC 2015) with high-resolution climate and land cover/land use information from Terra Populus (TerraPop) (MPC 2013). TerraPop allows summarizing raster-based spatial information (e.g., temperature and precipitation) for municipalities using harmonized boundary shapefiles (Kugler et al. 2015). The area summaries were then linked to census microdata records via unique municipality IDs, resulting in an analytical sample of 683,518 individuals residing in 2321 municipalities in 32 Mexican states.

The census recorded the municipality of residence during the enumeration year, and also collected information on individuals' municipality of residence five years prior. This information enabled us to return people to their municipality of residence five years prior to the census (hereafter, *origin*) and subsequently model internal out-migration in response to climate shocks.

Given that migration is highly concentrated at peak labor force ages (Rogers and Castro 1981) and substantially declines after age 39 in our sample, we focus our analysis on individuals ages 15–39 at the origin (Gray and Bilsborrow 2013; Mueller et al. 2014). Age at origin was computed by subtracting five years from the age recorded at the destination during the census interview. To

model migration between rural and urban municipalities, we obtained information on the percent of the area urban for each municipality based on Moderate Resolution Imaging Spectroradiometer (MODIS) urban extents for the year 2000 (Schneider et al. 2009), available from TerraPop. Based on a median split, we defined municipalities with no urban build up as rural (0.000% urban, light blue shading in Fig. 1a) and those with at least some urban build up as urban (0.001–78.3% urban, darker blue to violet shading in Fig. 1a) (see supplement S6 for a sensitivity analysis that uses a population-based classification of rural/urban status). The variable *urban origin* indicates the urbanization level of the origin municipality (for details see S2: Control variable construction). For migrants, we also differentiate between rural and urban destination municipalities (hereafter, *rural destination* and *urban destination*, respectively) at the end of a successful move, observed during the census year. The highest levels of urbanization are found in the central southwestern parts around Mexico City and along the coastline (Fig. 1a), while internal out-migration is more evenly distributed across Mexican municipalities (Fig. 1b).

For the computation of climate measures, we obtained a 50-year (1961–2010) time series of monthly average precipitation and maximum temperature. This information is available as high-resolution (0.5 degree) gridded data, constructed by the University of East Anglia's Climate Research Unit (CRU) (Harris et al. 2014) and summarized by TerraPop at the municipality level. The CRU data are considered the gold standard among modeled and unmodeled climate data sources (Zhang et al. 2013). Following Nawrotzki and Bakhtsiyarava (2016), we computed measures of drought and heat months during the 5-years prior to the census (during which migration occurred), plus 1 additional year to allow for a lagged migration response (Nawrotzki and DeWaard 2016). We computed the number of months during the observation period in which the maximum temperature was more than 1 standard deviation (SD) above and precipitation was more than 1 SD below the 30-year (1961–1990) climate normal reference period. These measures capture the cumulative exposure to climate extremes. As we show in Fig. 2, the largest number of drought months was observed in southern Mexico (Fig. 2a), while heat impacts were strongest in south central and northern regions of the country (Fig. 2b).

In addition to these core predictor variables, following previous research on climate migration (Gray and Bilsborrow 2013; Hunter et al. 2013; Nawrotzki et al. 2013), we constructed a comprehensive set of control variables to account for differences in gender, age, education, access to migrant networks, socioeconomic marginalization, agricultural dependence, access to irrigation infrastructure, baseline climatic conditions, and changes in the macro-economic context. Descriptive statistics of all variables employed in the present analysis are provided in Table 1, and detailed information on the construction of the control variables can be found in the supplementary material (S2: Control variable construction).

We employ multilevel models (Luke 2004) to account for the nested structure of our data in which climate effects operate at the municipality level and migration is measured for each individual. In this study, random effects models are preferred over fixed effects alternatives because they permit the inclusion of time-invariant municipality-level predictors, use fewer degrees of freedom, and allow for clustering of the standard errors at multiple levels. We estimate the log odds of internal migration to municipality r (urban or rural) relative to no migration, s , for individual i residing in municipality j in state k through a series of multinomial contrasts (Eq. 1).

$$\log\left(\frac{\pi_{rjk}}{\pi_{sjk}}\right) = \beta_0 + \beta_1(\text{drought}_{jk}) + \beta_2(\text{heat}_{jk}) + \beta_3(\text{urbo}_{jk}) + \beta_4(\text{drought}_{jk} \times \text{urbo}_{jk}) + \beta_5(\text{heat}_{jk} \times \text{urbo}_{jk}) + \beta_z(X_{zn}) + u_{jk} + v_k \quad (1)$$

We estimate two multinomial contrasts: (C1) migration to a rural destination, versus not migrating; and (C2) migration to an urban destination, versus not migrating (for technical details see supplement S3: Model fitting details). These models include the two climate measures ($drought_{jk}$ and $heat_{jk}$), an indicator variable for urban origin ($urbo_{jk}$ coded: 1 = urban, 0 = rural), and interactions between each climate measure and the urban origin indicator variable ($drought_{jk} \times urbo_{jk}$; $heat_{jk} \times urbo_{jk}$). Instead of stratifying the complete sample by urban/rural, we use interactions for increased power and parsimony of the statistical tests. The climate coefficients, β_1 and β_2 , reflect the effects of drought and heat in rural origins ($urbo_{jk} = 0$). For migration to rural destinations (C1), these coefficients refer to *rural-rural* migration. For migration to urban destinations (C2), these coefficients refer to *rural-urban* migration. Adding the climate and interaction coefficients (joint effect), we obtain the effects of drought ($\beta_1 + \beta_4$) and heat ($\beta_2 + \beta_5$) for urban origins ($urbo_{jk} = 1$). For migration to rural destinations (C1), the joint effects refer to *urban-rural* migration. For migration to urban destinations (C2), the joint effects refer to *urban-urban* migration. Significance tests are conducted for each effect, including post-estimation tests of the joint effects.

All models control for the effects (β_z) of various control variables (X_{zn}), operating at the individual-, municipality-, and state-levels, as indicated by the generic subscript n . Finally, the parameters u_{jk} and v_k are municipality and state random effects, which help to control for the nested data structure, differences in group size, and heteroskedastic error terms (Luke 2004).

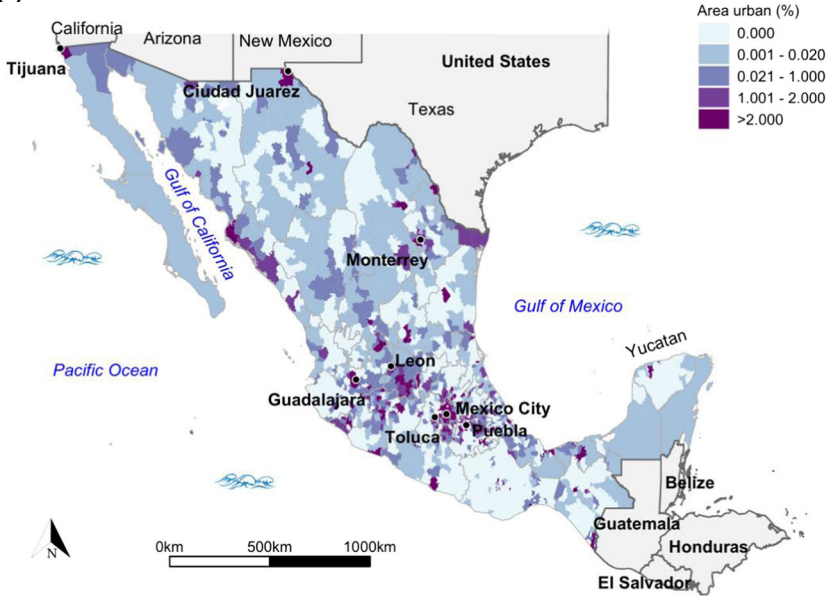
Employing the above model and contrasts, we test for nonlinear climate effects via quadratic and cubic specifications of the climate variables, and use these results to identify possible thresholds. The Bayesian Information Criterion (BIC) (Raftery 1995; Schwarz 1978) permits evaluating the model fit and, ultimately, to select the best specifications of our climate measures. As a rule of thumb, evidence that a model with a *lower* BIC provides a *better* fit, relative to a baseline model, is weak if $\Delta BIC = 0-2$, moderate if $\Delta BIC = 2-6$, strong if $\Delta BIC = 6-10$, and very strong if $\Delta BIC > 10$ (Raftery 1995).

3 Results

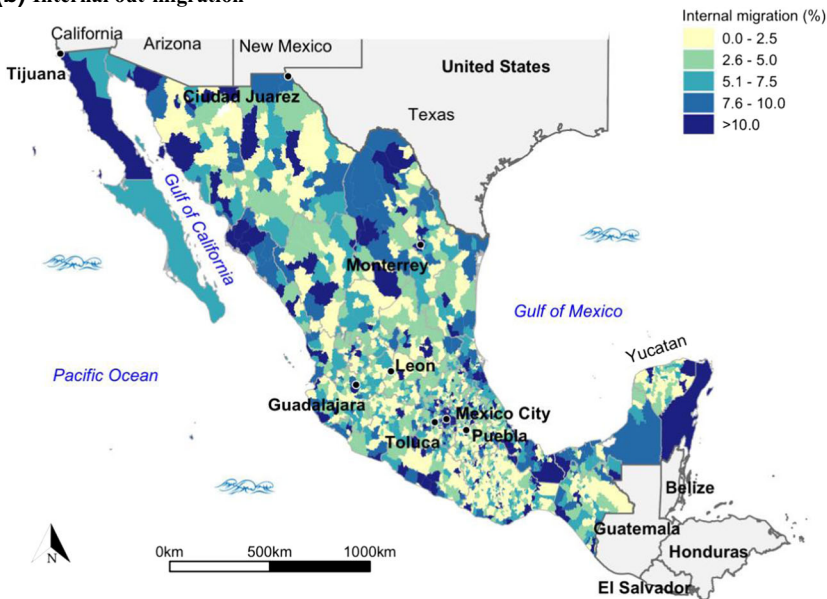
We began by estimating a baseline model to account for socioeconomic and contextual characteristics that influence internal migration in Mexico (see supplement S4; Table S1). Building on this model, Table 2 shows the results of adding the two climate measures (Model 1), an indicator variable for urban origin (Model 2), and interactions between each climate measure and the indicator variable for urban origin (Model 3). Models 4 and 5 are the multinomial contrasts for migration to rural and urban destinations, respectively. The coefficients in Table 2 permit the calculation of climate effects for each of the four migration streams between rural and urban municipalities. Figure 3 provides a visual representation of the predicted probabilities.

An increase in cumulative exposure to drought months is significant and positive associated with rural-rural migration ($\beta_1=0.23$ in Model 4, $p < 0.001$) and rural-urban migration ($\beta_1=0.31$ in Model 5, $p < 0.001$), but negatively associated with urban-urban migration ($\beta_1 + \beta_4=0.31-0.47 = -0.16$ in Model 5, $p < 0.001$) and shows no significant association with urban-rural migration ($\beta_1 + \beta_4=0.23-0.25 = -0.02$ in Model 4, n.s.). In contrast, an increase in cumulative exposure to heat months is significant and negatively associated with rural-rural migration

(a) Percent area urban



(b) Internal out-migration

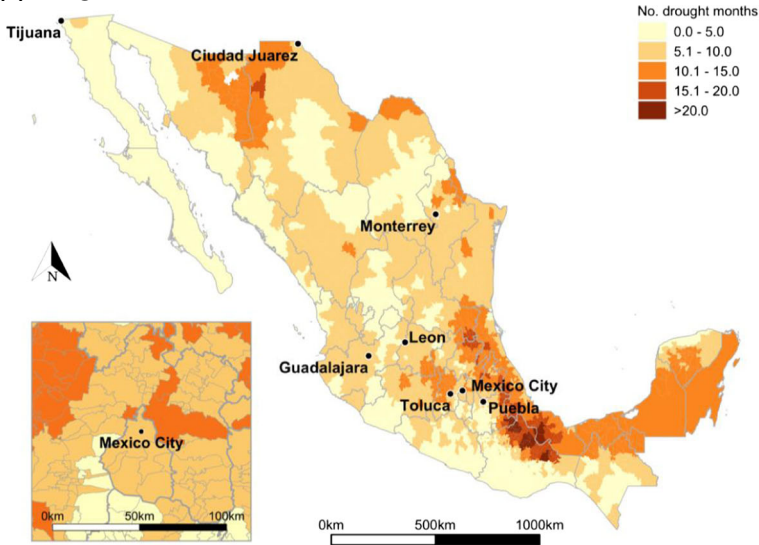


Notes: Maps and figures were generated using the R package *ggplot2* (Wickham 2009). Source: Internal out-migration rates were computed based on census microdata obtained via IPUMS International (MPC 2015). Percent area urban derived from TerraPop (MPC 2013; Kugler et al. 2015) and based on MODIS urban extents (approximately year 2000) (Schneider et al. 2009).

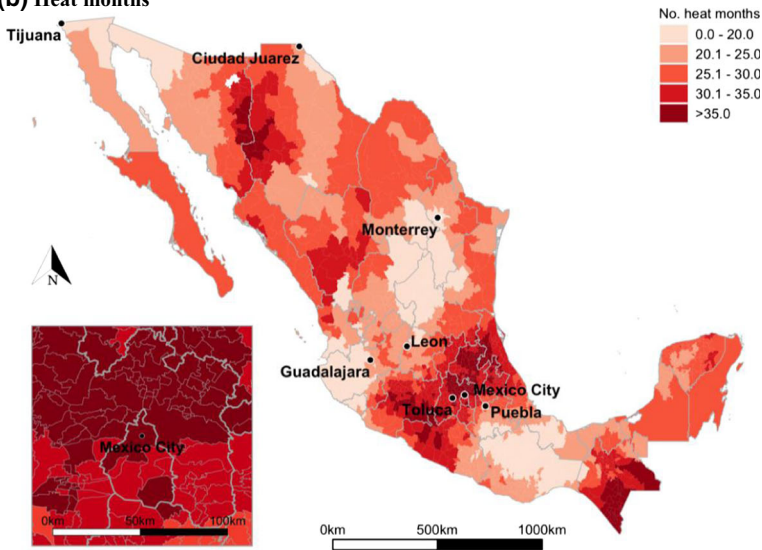
Fig. 1 Spatial distribution of the percent area urban (approximately for the year 2000) and internal out-migration rates (average for the years 2000 and 2010) for Mexican municipalities

($\beta_2 = -0.20$ in Model 4, $p < 0.001$), rural-urban migration ($\beta_2 = -0.11$ in Model 5, $p < 0.001$), and urban-rural migration ($\beta_2 + \beta_5 = -0.20 + 0.08 = -0.12$ in Model 4, $p < 0.001$), but has no

(a) Drought months



(b) Heat months



Notes: Insets provide a close-up view for the area surround Mexico City, the largest urban center in the country and prime destination for internal migrants. Source: Number of drought and heat months computed from monthly precipitation and temperature records derived from TerraPop (MPC 2013; Kugler et al. 2015) and based on high-resolution gridded climate data from the University of East Anglia’s Climate Research Unit (CRU) (Harris et al. 2014).

Fig. 2 Spatial distribution of drought and heat months (mean values across climate measures computed for census years 2000 and 2010) for Mexican municipalities

effect on urban-urban migration ($\beta_2 + \beta_5 = -0.11 + 0.12 = 0.01$ in Model 5, n.s.). In response to our first research question, climate shocks clearly influence rural-urban migration and to a lesser degree other internal migration streams in Mexico.

Table 1 Descriptive statistics of variables employed in the analysis of climate shocks on internal migration in Mexico during 2000 and 2010

	Unit	TV	Min	Max	Mean	SD
Outcome variables (individual level)						
Migrant	1 0	Yes	0	1	0.07	0.25
Migrant to rural destination	1 0	Yes	0	1	0.02	0.13
Migrant to urban destination	1 0	Yes	0	1	0.05	0.22
Climate variables (municipality level)						
Drought months	count	Yes	0	26	8.18	5.22
Heat months	count	Yes	3	59	24.73	8.49
Control variables (individual/household level)						
Male	1 0	Yes	0	1	0.47	0.50
Age	years	Yes	15	39	25.81	7.12
Education	years	Yes	0	18	8.04	4.40
International migrant household	1 0	Yes	0	1	0.05	0.21
Control variables (municipality level)						
Urban origin	1 0	No	0	1	0.36	0.48
Migrant networks (domestic)	%	Yes	0	100	3.73	5.24
Migrant networks (international)	z-scores	Yes	-1.16	6.4	0.04	1.00
Marginalization index	z-scores	Yes	-2.18	3.79	0.03	0.98
Agriculture employment	%	Yes	0	89.47	19.81	12.24
Corn area harvested	sqm / 10 ha	No	0	10.2	1.19	1.30
Wheat area harvested	sqm / 10 ha	No	0	4.06	0.06	0.21
Irrigated cropland	%	No	0	100	18.87	26.84
Baseline max temp (1961–90)	deg. C	No	20.75	35.42	27.26	3.09
Baseline precip (1961–90)	mm	No	7.43	268.56	86.46	45.72
Control variables (state level)						
GDP change	%	Yes	-0.51	9.1	3.11	1.79
Sample size						
Individuals					683,518	
Municipalities					2321	
States					32	

TV = measure varies across censuses (yes), measure is constant across censuses (no); Source: IPUMS International was the primary source of population data while most geographic municipality information was derived from TerraPop and INEGI as detailed in the supplementary material (S2: Control variable construction)

Odds ratios ($OR = \exp(\beta)$) and predicted probabilities ($P = 1/(1 + \exp(-\beta))$) can be calculated to provide a more intuitive sense of the directions and magnitudes of these associations (Singer and Willett 2003). For example, each additional drought month increases the odds of rural-urban migration by 3.6% ($(\exp(0.31)-1)*10$), while each additional heat month decreases the odds of rural-urban migration by 1.0% ($(\exp(-0.11)-1)*10$). As shown in Fig. 3, the corresponding predicted probabilities of rural-urban migration (blue series) increase by 0.017 over the observed range of 26 drought months (Fig. 3b) and decrease by 0.01 over the observed range of 59 heat months (Fig. 3f).

To test for nonlinearities and explore thresholds in the relationships between climate shocks and the four internal migration streams, we further estimated the effects of quadratic and cubic

transformations of drought and heat months. We began by estimating models using the same transformation for both climate predictors (see supplement S5, Table S2). However, because drought and heat effects may exhibit different nonlinear patterns (Bohra-Mishra et al. 2014; Joseph et al. 2014), we estimated models that exploited all possible combinations of linear, quadratic, and cubic specifications. In Table 3, we report differences in the BIC statistics for models including each combination of specifications relative to the default *linear-linear* specification (top left cells in Tables 3a and b). The best fitting model is highlighted in grey.

For migration to rural destinations (Table 3a), the linear-linear specification produces the lowest BIC statistic, although it is worth noting that the model using a quadratic specification of drought months in combination with a linear specification of heat months shows only a slightly worse fit with an increase in BIC by 0.1 points. For migration to urban destinations (Table 3b), there is clear evidence of a nonlinear relationship. The model using a linear specification for drought months and a quadratic specification for heat months produces a BIC statistic that is 22 points lower than the default linear-linear specification, indicating superior model fit. Tables of parameter estimates for the best fitting models are reported in the supplementary material (Table S3).

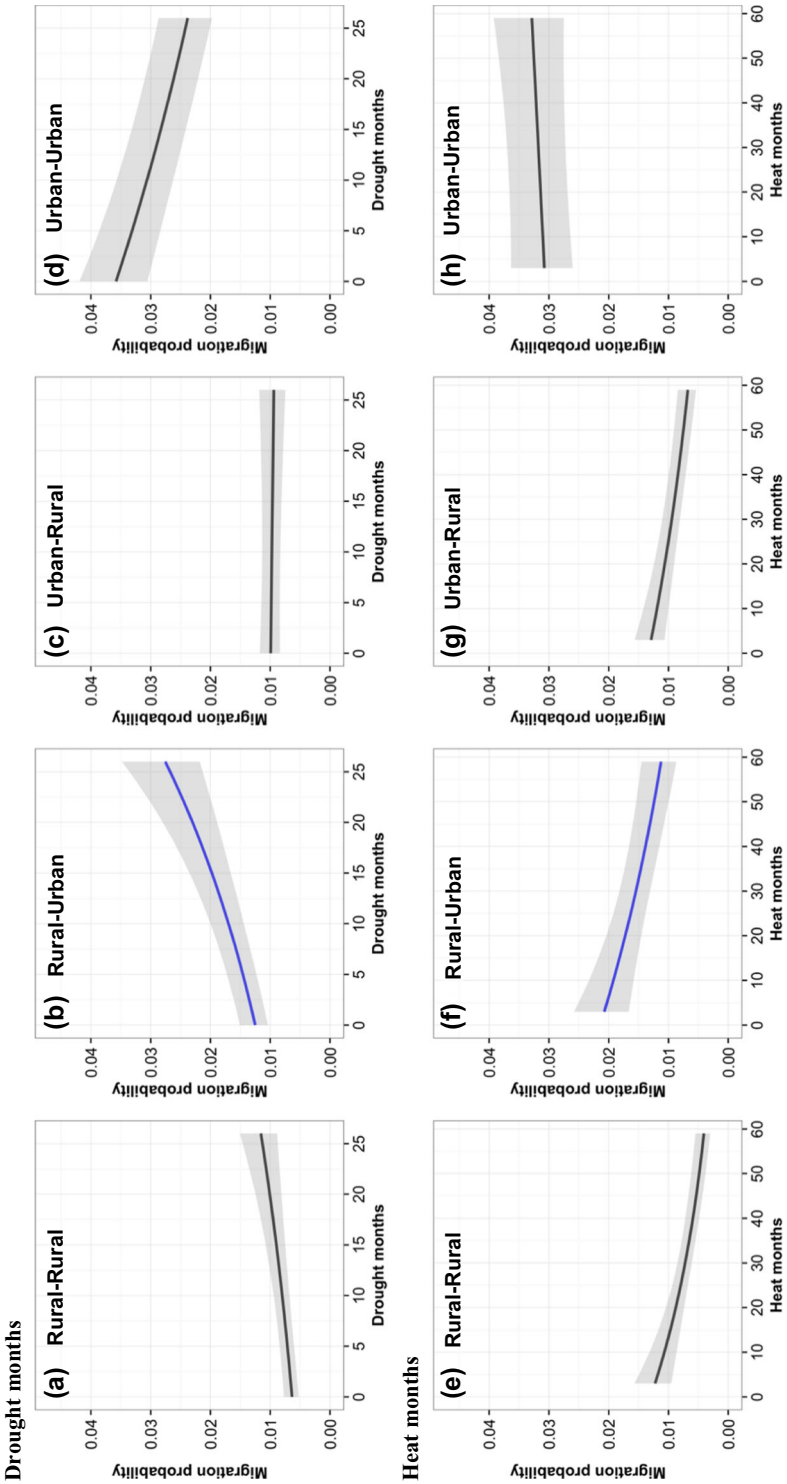
Plotting the predicted probabilities for the best fitting models (Fig. 4) shows similar patterns to those reported earlier (Fig. 3) with the exceptions of rural-urban and urban-urban migration in response to heat months (Fig. 4f and h). An increase in heat months initially leads to a decrease in rural-urban migration until an inflection point is reached at ~34 months, beyond which the relationship becomes increasingly positive. A similar, but less pronounced pattern

Table 2 Linear effects of climate shocks on internal outmigration to all (rural and urban) destinations (Models 1–3), to rural destinations (Model 4), and urban destinations (Model 5) in Mexico during 2000 and 2010

Variables	Model 1		Model 2		Model 3		Model 4		Model 5	
	All moves		All moves		All moves		Rural destination		Urban destination	
	b	sig.	b	sig.	b	sig.	b	sig.	b	sig.
Drought months (β_1)	-0.01		-0.01		0.24	***	0.23	***	0.31	***
Heat months (β_2)	-0.04	**	-0.04	**	-0.10	***	-0.20	***	-0.11	***
Urban origin (β_3)			0.56	***	0.56	***	0.25	***	0.70	***
Drought months x Urban origin (β_4)					-0.34	***	-0.25	***	-0.47	***
Heat months x Urban origin (β_5)					0.10	***	0.08		0.12	***
Model statistics										
Variance (municipality)	0.604		0.568		0.579		0.894		0.674	
Variance (state)	0.079		0.054		0.056		0.116		0.146	
BIC	302,002		301,874		301,826		107,563		238,004	
N (individuals)	683,518		683,518		683,518		649,570		671,637	
N (municipalities)	2321		2321		2321		2321		2321	
N (states)	32		32		32		32		32	

Parameter estimates reflect log odds; Coefficients of climate variables reflect an incremental change of 10 units; climate variables were grand mean centered; All models were estimated using the complete set of control variables (see Supplement Table S1) but these coefficients are not shown to preserve space; Models 1–3 were estimated as regular logit models while Models 4 and 5 were estimated as multinomial logit models;

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$



Notes: Predicted probabilities were computed for the average migrant in the sample (mean value for all control variables). 95% confidence bands for the predictions are shown in grey. Sub-figures (a & c) and (e & g) were based on predictions from Model 4 (Table 2), while sub-figures (b & d) and (f & h) were based on predictions from Model 5 (Table 2). Only slopes from the same model can directly be compared.

Fig. 3 Predicted probabilities of internal out-migration in response to linear changes in drought months and heat months

holds for urban-urban migration. We subsequently performed a number of sensitivity tests, which demonstrated a high degree of robustness of the reported relationships (see supplement S6: Sensitivity tests).

4 Discussion

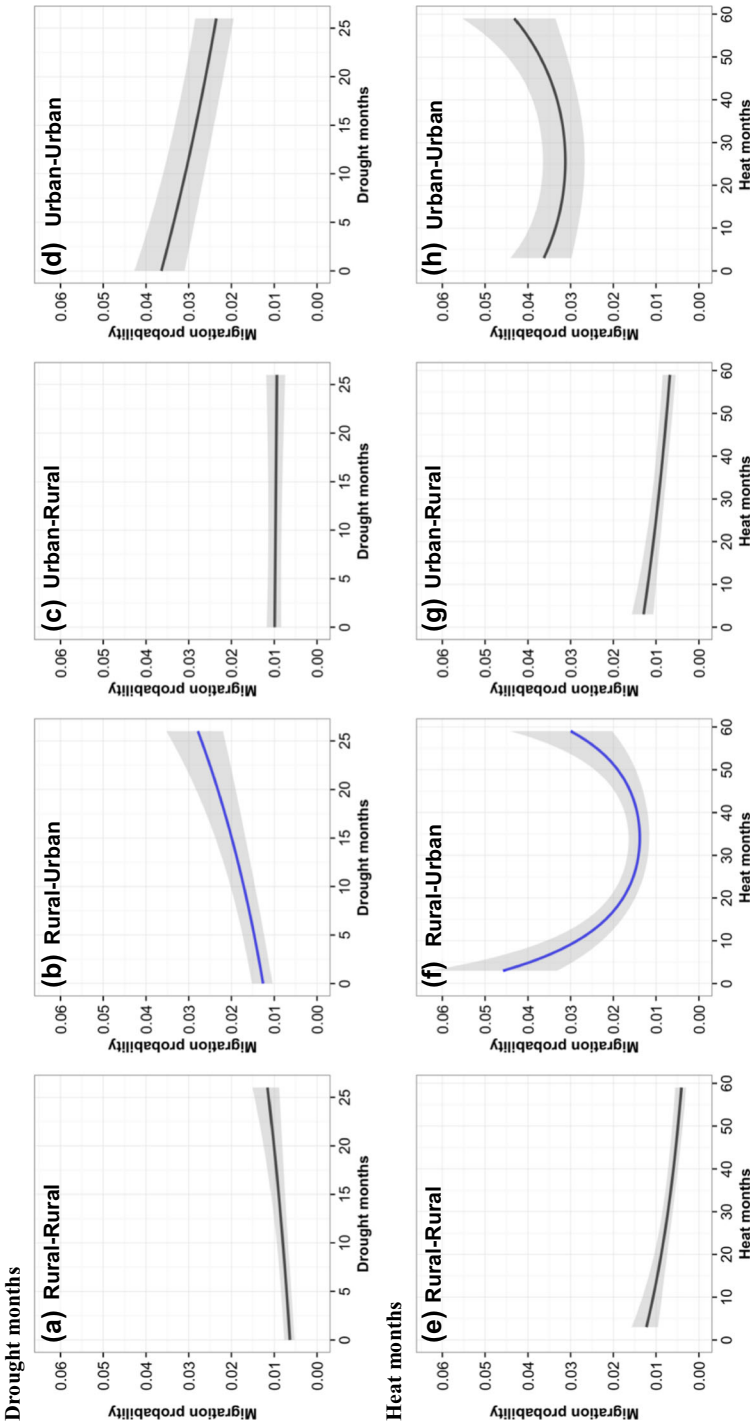
This research constitutes the first empirical study of internal migration in response to climate shocks in Mexico, with particular focus on migration between rural and urban areas and the identification of nonlinearities and thresholds in the climate-migration relationship. For most internal migration flows, linear specifications of our two climate measures produced the best fitting models. However, we also detected important nonlinearities in the relationship between cumulative exposure to heat months and migration to urban destinations. Migration to rural destinations (e.g., rural-rural, urban-rural) is only weakly associated with climate factors. We therefore focus the following discussion on migration to urban areas, specifically rural-urban migration due its policy relevance. Our measures of cumulative exposure to climate extremes are highly correlated with alternative measures of the magnitude of climate shocks and the spell length (see supplement S6: Sensitivity tests), thereby permitting comparison with more traditional measures of temperature and precipitation.

Our detection of a positive association between cumulative exposure to drought months and rural-urban migration is in line with prior research on international climate migration documenting increases in international moves under conditions of declining rainfall and droughts (Barrios Puente et al. 2015; Hunter et al. 2013; Nawrotzki et al. 2013). Droughts can adversely impact crop production and undermine agriculture-based income generation and employment opportunities in rural areas (Feng and Oppenheimer 2012). Under conditions of adverse climatic change and associated declines in livelihood security, individuals in rural areas may choose to relocate to urban areas in search of non-agricultural employment opportunities. Although rural-rural migration is also an option, we find that rural-urban migration is a more common response to droughts, as indicated by the much steeper slope in the relationship between drought months and rural-urban (vs. rural-rural) migration. Our

Table 3 Difference in model fit statistics (BIC) for various combinations of linear and nonlinear specifications of drought and heat months predicting internal migration to rural (a) and urban (b) destinations in Mexico during 2000 and 2010

		(a) Rural destination			(b) Urban destination		
		Drought months			Drought months		
		Linear	Quadratic	Cubic	Linear	Quadratic	Cubic
Heat months	Linear	0.0	0.1	11.3	0.0	6.2	9.7
	Quadratic	13.5	12.5	23.5	-22.0	-15.3	-13.9
	Cubic	32.6	31.8	42.2	-2.4	5.6	6.6

Models were estimated similar to supplement Table S2 with different combinations of linear, quadratic, and cubic terms for the climate predictors; Values reflect differences in BIC relative to the default linear-linear specification (top left cells); a positive value reflects an increase in BIC (worse model fit), while a negative value reflects a decrease in BIC (improved model fit). The cell indicating the best fitting combination is highlighted grey



Notes: Predicted probabilities were computed for the average migrant in the sample (mean value for all control variables). 95% confidence bands for the predictions are shown in grey. Sub-figures (a & c) and (e & g) were based on predictions from the rural destination model (supplement Table S3), while sub-figures (b & d) and (f & h) were based on predictions from the urban destination model (supplement Table S3). Only slopes from the same model can directly be compared.

Fig. 4 Predicted probabilities of internal out-migration in response to linear and non-linear changes in drought months and heat months obtained from the best fitting models (supplement Table S3)

study therefore breaks new ground by providing the first empirical evidence that droughts differentially and disproportionately drive rural-urban internal migration in Mexico.

With respect to temperature effects, we find that an increase in heat months is likewise associated with rural-urban migration, but in a nonlinear fashion. We found evidence for a U-shaped, quadratic functional form, similar to studies of temperature and internal migration in Yemen (Joseph et al. 2014) and Indonesia (Bohra-Mishra et al. 2014). A moderate increase in heat months is associated with a decrease in rural-urban migration until ~34 months (47% of the 72 months observation period). With a further increase in heat months, this relationship becomes increasingly positive, resulting in higher out-migration under warming conditions. Although our study employs measures of cumulative heat exposure that differ from crude temperature measures or degree days used in agronomic research, this nonlinear relationship can be explained substantively by considering agricultural pathways (Nawrotzki and Bakhtsiyarava 2016; Stark and Bloom 1985). An increase in the number of months with warmer temperatures may initially lead to higher crop yields due to increased plant metabolism and longer growing seasons (Mendelsohn 2007). Under favorable climatic conditions of an extended period of warm months and sufficient rainfall, individuals may invest their efforts in agricultural production at home instead of migrating, evidenced by the initial decrease in mobility (Ward and Shively 2015). However, once the optimal temperature has been surpassed and cumulative heat exposure becomes severe, crop yields can decline dramatically (Sanchez et al. 2014). Individuals may therefore choose to migrate to urban areas to seek employment in non-agricultural occupations, resulting in an increase in the probability of migration at the upper range of the cumulative heat-months exposure spectrum. Additionally, in response to extended heat periods, economic losses may occur in the nonagricultural sector due to a decline in labor productivity (Hsiang 2010), which helps to explain the observed upward trend in urban-urban migration.

Keeping the limitations of this study in mind (see supplement S7: Limitations), our findings have important policy implications. Future projections for Mexico suggest a warming in temperatures (Romero-Lankao et al. 2014) and an increase in the frequency and severity of droughts (Wehner et al. 2011). Our results demonstrate that increases in cumulative exposure to drought and heat months at the upper ends of these distributions can substantially increase rural-urban migration and, to a lesser extent, other migration streams in Mexico. These migration patterns will be potentially consequential for changes in population size and density, infrastructure and resource access, and the capacity to deliver essential goods and services in urban areas (Adamo 2010). Policy and programmatic interventions should therefore be designed and implemented to assist migrants from rural areas in finding employment and housing in urban areas to prevent, for example, increases in unemployment and/or the growth of shantytowns and urban slums.

The implementation of livelihood-based climate adaptation programs may also help to prevent excessive migration from rural areas due to climate factors. Climate adaptation programs might include, for example, financing the construction of small-scale irrigation systems (Burney et al. 2013), distribution of climate monitoring and warning systems (Cooper et al. 2008), support for selective breeding of local crop varieties, and facilitating the exchange of crop varieties between agro-ecological zones (Mercer et al. 2012). Such programs will not only improve livelihoods and thereby prevent migration from rural areas, but, in the process, will provide incentives to maintain a sizable rural labor force to guarantee sufficient food production for the entire country.

In conclusion, our study has shown that adverse climate impacts led to increased internal migration in Mexico in 2000 and 2010. Higher levels of cumulative exposure to drought and heat months differentially drove rural-urban migration. Planners and policy

makers, especially those in urban areas, should therefore prepare for increased inflows of migrants from rural areas in response to climate variability and change in future decades.

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Compliance with ethical standards

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Conflict of interest The authors declare that they have no conflict of interest.

References

- Adamo SB (2010) Environmental migration and cities in the context of global environmental change. *Curr Opin Environ Sustain* 2:161–165. doi:10.1016/j.cosust.2010.06.005
- Adger WN (2006) Vulnerability. *Glob Environ Change-Human Policy Dimens* 16:268–281. doi:10.1016/j.gloenvcha.2006.02.006
- Aguiayo-Tellez E, Martínez-Navarro J (2013) Internal and international migration in Mexico: 1995–2000. *Appl Econ* 45:1647–1661. doi:10.1080/00036846.2011.633894
- Bardsley DK, Hugo GJ (2010) Migration and climate change: examining thresholds of change to guide effective adaptation decision-making. *Popul Environ* 32:238–262. doi:10.1007/s11111-010-0126-9
- Barrios Puente G, Perez F, Gitter RJ (2015) The effect of rainfall on migration from Mexico to the U.S. *International Migration Review* online. doi:10.1111/imre.12116
- Barrios S, Bertinelli L, Strobl E (2006) Climatic change and rural-urban migration: the case of sub-Saharan Africa. *J Urban Econ* 60:357–371. doi:10.1016/j.jue.2006.04.005
- Bodvarsson O, Van den Berg H (2009) *The economics of immigration*. Springer, Heidelberg, Germany
- Bohra-Mishra P, Oppenheimer M, Hsiang SM (2014) Nonlinear permanent migration response to climatic variations but minimal response to disasters. *Proc Natl Acad Sci U S A* 111:9780–9785. doi:10.1073/pnas.1317166111
- Burney J, Naylor R, Postel S (2013) The case for distributed irrigation as a development priority in sub-Saharan Africa. *Proc Natl Acad Sci U S A* 110:12513–12517. doi:10.1073/pnas.1203597110
- Charlton D, Taylor JE (2013) Mexicans are leaving farm work: what does it mean for U.S. agriculture and immigration policy? *Agricultural and Resource Economics Update* 16:1–4
- Collins M et al (2013) Long-term climate change: projections, commitments and irreversibility. In: Stocker TF et al (eds) *Climate change 2013: the physical science basis*. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, pp. 1029–1136
- Conde C, Ferrer R, Orozco S (2006) Climate change and climate variability impacts on rainfed agricultural activities and possible adaptation measures. A Mexico case study *Atmosfera* 19:181–194
- Cooper PJM, Dimes J, Rao KPC, Shapiro B, Shiferaw B, Twomlow S (2008) Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? *Agric Ecosyst Environ* 126:24–35. doi:10.1016/j.agee.2008.01.007

- Dillon A, Mueller V, Salau S (2011) Migratory responses to agricultural risk in northern Nigeria. *Am J Agric Econ* 93:1048–1061. doi:10.1093/ajae/aar033
- Feng S, Oppenheimer M (2012) Applying statistical models to the climate-migration relationship. *Proc Natl Acad Sci* 109:E2915
- Findlay AM (2011) Migrant destinations in an era of environmental change. *Glob Environ Change-Human Policy Dimens* 21:S50–S58. doi:10.1016/j.gloenvcha.2011.09.004
- Gray CL, Bilborrow R (2013) Environmental influences on human migration in rural Ecuador. *Demography* 50:1217–1241. doi:10.1007/s13524-012-0192-y
- Gray CL, Wise E (2016) Country-specific effects of climate variability on human migration. *Clim Chang* 135:555–568. doi:10.1007/s10584-015-1592-y
- Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 dataset. *Int J Climatol* 34:623–642. doi:10.1002/joc.3711
- Hsiang SM (2010) Temperatures and cyclones strongly associated with economic production in the Caribbean and central America. *Proc Natl Acad Sci U S A* 107:15367–15372. doi:10.1073/pnas.1009510107
- Hunter LM, Luna JK, Norton RM (2015) Environmental dimensions of migration. *Annu Rev Sociol* 41:377–397. doi:10.1146/annurev-soc-073014-112223
- Hunter LM, Murray S, Riosmena F (2013) Rainfall patterns and U.S. migration from rural Mexico. *Int Migr Rev* 47:874–909
- IPCC (2014) Summary for policymakers. In: Field CB et al. (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York, pp 1–32
- Joseph G, Wodon Q, Liverani A, Blankespoor B (2014) Is climate change likely to lead to higher net internal migration? The republic of Yemen's case. In: Wodon Q, Liverani A, Joseph G, Bougnoux N (eds) *Climate change and migration: evidence from the Middle East and North Africa*. The World Bank, Washington, D.C., pp 191–204. doi:10.1596/978-0-8213-9971-2
- Kugler TA, Van Riper DC, Manson SM, Haynes DA, Donato J, Stinebaugh K (2015) Terra Populus: workflows for integrating and harmonizing geospatial population and environmental data. *Journal of Map and Geography Libraries* 11:180–206. doi:10.1080/15420353.2015.1036484
- Luke DA (2004) *Multilevel modeling. Quantitative applications in the social sciences* 143. Sage Publications, Inc, Thousand Oaks, CA
- Massey DS (1987) Understanding Mexican migration to the United-States. *Am J Sociol* 92:1372–1403. doi:10.1086/228669
- Massey DS, Espinosa KE (1997) What's driving Mexico-US migration? A theoretical, empirical, and policy analysis. *Am J Sociol* 102:939–999. doi:10.1086/231037
- Mberu BU (2005) Who moves and who stays? Rural out-migration in Nigeria. *J Popul Res* 22:141–161
- McLeman R, Opatowski M, Borova B, Walton-Roberts M (2016) Laurier US embassy workshop on environmental migration and displacement: workshop report. Balsillie school of international affairs. Waterloo, Canada
- McSweeney C, New M, Lizcano G (2008) *UNDP climate change country profiles: Mexico*. United Nations Development Programme, New York
- Mendelsohn R (2007) What causes crop failure? *Clim Chang* 81:61–70. doi:10.1007/s10584-005-9009-y
- Mercer KL, Perales HR, Wainwright JD (2012) Climate change and the transgenic adaptation strategy: smallholder livelihoods, climate justice, and maize landraces in Mexico. *Glob Environ Change-Human Policy Dimens* 22:495–504. doi:10.1016/j.gloenvcha.2012.01.003
- MPC (2013) *Terra Populus: Beta version [machine-readable database]*. University of Minnesota, Minneapolis, MN, Minnesota Population Center
- MPC (2015) *Integrated Public Use Microdata Series, International: Version 6.4 [Machine-readable database]*. University of Minnesota, Minneapolis
- Mueller V, Gray CL, Kosec K (2014) Heat stress increases long-term human migration in rural Pakistan. *Nat Clim Chang* 4:182–185. doi:10.1038/nclimate2103
- Nawrotzki RJ, Bakhtsiyarava M (2016) International climate migration: evidence for the climate inhibitor mechanism and the agricultural pathway. *Population, Space & Place Online*, pp. 1–16. doi:10.1002/psp.2033
- Nawrotzki RJ, DeWaard J (2016) Climate shocks and the timing of migration from Mexico. *Popul Environ* 38:72–100. doi:10.1007/s11111-016-0255-x
- Nawrotzki RJ, Hunter LM, Runfola DM, Riosmena F (2015a) Climate change as migration driver from rural and urban Mexico. *Environ Res Lett* 10:1–9. doi:10.1088/1748-9326/10/1/114023

- Nawrotzki RJ, Riosmena F, Hunter LM (2013) Do rainfall deficits predict U.S.-bound migration from rural Mexico? Evidence from the Mexican census. *Popul Res Policy Rev* 32:129–158. doi:[10.1007/s11113-012-9251-8](https://doi.org/10.1007/s11113-012-9251-8)
- Nawrotzki RJ, Riosmena F, Hunter LM, Runfola DM (2015b) Amplification or suppression: social networks and the climate change-migration association in rural Mexico. *Glob Environ Chang* 35: 463–474. doi:[10.1016/j.gloenvcha.2015.09.002](https://doi.org/10.1016/j.gloenvcha.2015.09.002)
- Raftery AE (1995) Bayesian model selection in social research. *Sociol Methodol* 25:111–163. doi:[10.2307/271063](https://doi.org/10.2307/271063)
- Ratha D, Mohapatra S, Oezden C, Plaza S, Shaw W, Shimeles A (2011) Leveraging migration for Africa: remittances, skills, and investments. World Bank, Washington, DC
- Rogers A, Castro L (1981) Model migration schedule. IIASA Research Report RR-81-030. International Institute for Applied Systems Analysis, Laxenburg, Austria
- Romero-Lankao P (2010) Water in Mexico City: what will climate change bring to its history of water-related hazards and vulnerabilities? *Environ Urban* 22:157–178. doi:[10.1177/0956247809362636](https://doi.org/10.1177/0956247809362636)
- Romero-Lankao P et al. (2014) North America. In: Barros VR et al. (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York, pp 1439–1498
- Runfola DM, Romero-Lankao P, Jiang L, Hunter LM, Nawrotzki RJ, Sanchez L (2016) The influence of internal migration on exposure to extreme weather events in Mexico. *Soc Nat Resour* 29:750–754. doi:[10.1080/08941920.2015.1076918](https://doi.org/10.1080/08941920.2015.1076918)
- Sanchez B, Rasmussen A, Porter JR (2014) Temperatures and the growth and development of maize and rice: a review. *Glob Chang Biol* 20:408–417. doi:[10.1111/gcb.12389](https://doi.org/10.1111/gcb.12389)
- Schneider A, Friedl M, Potere D (2009) A new map of global urban extent from MODIS satellite data. *Environ Res Lett* 4:1–11. doi:[10.1088/1748-9326/4/4/044003](https://doi.org/10.1088/1748-9326/4/4/044003)
- Schwarz G (1978) Estimating the dimension of a model. *The Journal of Statistics* 6:461–464
- Scoones I (1999) *Sustainable rural livelihoods: a framework for analysis*. Institute of Development Studies, Brighton, UK
- Scott J (2007) *Agricultural policy and rural poverty in Mexico*. Centro de Investigación y Docencia Económicas (CIDE), Mexico City
- Singer JD, Willett JB (2003) *Applied longitudinal data analysis: modeling change and event occurrence*. Oxford University Press, New York
- Stark O, Bloom DE (1985) The new economics of labor migration. *Am Econ Rev* 75:173–178
- Ward PS, Shively GE (2015) Migration and land rental as responses to income shocks in rural China. *Pac Econ Rev* 20:511–543. doi:[10.1111/1468-0106.12072](https://doi.org/10.1111/1468-0106.12072)
- Wehner M, Easterling DR, Lawrimore JH, Heim RR Jr, Vose RS, Santer BD (2011) Projections of future drought in the continental United States and Mexico. *J Hydrometeorol* 12:1359–1377. doi:[10.1175/2011jhm1351.1](https://doi.org/10.1175/2011jhm1351.1)
- Wickham H (2009) *ggplot2: elegant graphics for data analysis*. Springer, New York
- Wiggins S, Keilbach N, Preibisch K, Proctor S, Herrejon GR, Munoz GR (2002) Discussion - agricultural policy reform and rural livelihoods in Central Mexico. *J Dev Stud* 38:179–202. doi:[10.1080/00220380412331322461](https://doi.org/10.1080/00220380412331322461)
- Winters P, Davis B, Corral L (2002) Assets, activities and income generation in rural Mexico: factoring in social and public capital. *Agric Econ* 27:139–156
- Zhang Q, Komich H, Holmgren K (2013) How well do reanalyses represent the southern African precipitation? *Clim Dyn* 40:951–962. doi:[10.1007/s00382-012-1423-z](https://doi.org/10.1007/s00382-012-1423-z)