

# Linkages among climate change, crop yields and Mexico–US cross-border migration

Shuaizhang Feng<sup>a,b</sup>, Alan B. Krueger<sup>a,c,d</sup>, and Michael Oppenheimer<sup>a,e,1</sup>

<sup>a</sup>Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544; <sup>b</sup>School of Economics, Shanghai University of Finance and Economics, Shanghai 200433, China; Departments of <sup>c</sup>Economics and <sup>d</sup>Geosciences, Princeton University, Princeton, NJ 08544; and <sup>e</sup>US Department of Treasury, Washington, DC 20220

Edited\* by Stephen H. Schneider, Stanford University, Stanford, CA, and approved June 24, 2010 (received for review March 3, 2010)

Climate change is expected to cause mass human migration, including immigration across international borders. This study quantitatively examines the linkages among variations in climate, agricultural yields, and people's migration responses by using an instrumental variables approach. Our method allows us to identify the relationship between crop yields and migration without explicitly controlling for all other confounding factors. Using state-level data from Mexico, we find a significant effect of climate-driven changes in crop yields on the rate of emigration to the United States. The estimated semielasticity of emigration with respect to crop yields is approximately  $-0.2$ , i.e., a 10% reduction in crop yields would lead an additional 2% of the population to emigrate. We then use the estimated semielasticity to explore the potential magnitude of future emigration. Depending on the warming scenarios used and adaptation levels assumed, with other factors held constant, by approximately the year 2080, climate change is estimated to induce 1.4 to 6.7 million adult Mexicans (or 2% to 10% of the current population aged 15–65 y) to emigrate as a result of declines in agricultural productivity alone. Although the results cannot be mechanically extrapolated to other areas and time periods, our findings are significant from a global perspective given that many regions, especially developing countries, are expected to experience significant declines in agricultural yields as a result of projected warming.

human migration | global warming | environmental migrants | agricultural productivity | instrumental variables approach

Climate change presents many critical challenges to humankind (1, 2). One widely cited impact is the displacement of large numbers of people (3–9). Among all potential “climate refugees” or “environmental migrants,” those crossing international borders are likely to be of particular concern for both developing (in many cases, migrant-sending) and developed (i.e., migrant-receiving) countries. Although migration is a normal part of the development process (10, 11), and can be an important risk management strategy for households (12, 13), unmanaged and unexpected climate-related migration could exacerbate a range of problems, including deterioration of ecosystems, slowing of regional economic development, disruption of human and political rights, and increased international conflicts and border fortification (14).

Despite qualitative assertions and some local case studies (7, 8, 15, 16) (*SI Appendix, part 1*), climate-driven migration has not received sufficient attention in the immigration literature. Existing studies of immigration typically emphasize the roles of geographic proximity, relative economic opportunities for potential migrants, social and cultural networks, and political stability as causative factors. Climate factors may play an increasingly important role in the future, given the prospect of global warming. Although the underlying climate/migration relationship is complex and the evidence is sometimes elusive (8, 17–19), policymakers require plausible forecasts to prepare for future immigration flows in response to climate change. For that reason, this study uses an approach that isolates the climate effect—which may have only been secondary—from other drivers of historical migration to provide a basis for the estimation of future international immigration flows.

Several aspects of climate change may drive changes in migration (20). In this study, we focus on the climate acting through its effect on agricultural productivity. Changes in crop yields that result from climate change occur over broad geographical areas (unlike sea level rise, which directly affects only coastal regions), and are likely to lead to long-term population shifts (more so than episodic flooding, for instance, the effects of which tend to be transitory). Such a phenomenon is especially relevant to developing countries, which typically have large rural populations that derive a living directly from agriculture. Lacking resources to adapt, developing countries are also most vulnerable to future warming (21, 22). Furthermore, the possible impacts of climate change on the agriculture sector have been estimated worldwide and are relatively well understood (23–25).

Specifically, we study Mexico for the decade of 1995 to 2005, during which time a substantial increase in out-migration to the United States occurred. Studies have examined numerous factors underlying the so called “great Mexican emigration” (26–31), including negative labor demand shocks, labor supply shocks resulting from demographic changes, US immigration policy changes, migrant networks, and importation of cheap corn and other agricultural products following the North American Free Trade Agreement (NAFTA) (32). Yet to our knowledge no study has directly associated a component of the increase in emigration with changes in climate, despite numerous reports and anecdotes of Mexican farmers fleeing to the United States because they no longer could maintain their previous way of life because of climate-driven crop failures (8, 33). This omission is significant given that the period after 1994 also coincides with a historically rare period of drought in much of Mexico, especially in the north, that is comparable to the great Mexican drought of the 1950s (34).

We chose Mexico for our study because it is one of the biggest migrant-source countries, because there exists state-level data on emigration, and because it has undergone diverse degrees of climate variability across regions. In addition, Mexico is unique in that the relative ease of migration to the United States allows us to better capture the full potential emigration response to changes in crop yields than in many other cases. It is extremely important for policymakers to appreciate the magnitude of the “desired” or “potential” demand for out-migration when evaluating various policy options.

To estimate the sensitivity of emigration to crop yields, we employ a statistical estimator that uses only the portion of variations in crop yields across states that is predicted by variations in climate. Such yield variations, unlike those caused, for example,

Author contributions: S.F., A.K., and M.O. designed research; S.F., A.K., and M.O. performed research; S.F. analyzed data; and S.F., A.K., and M.O. wrote the paper.

The authors declare no conflict of interest.

\*This Direct Submission article had a prearranged editor.

Freely available online through the PNAS open access option.

<sup>1</sup>To whom correspondence should be addressed. E-mail: omichael@princeton.edu.

This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1002632107/-DCSupplemental](http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1002632107/-DCSupplemental).

by policy-related environmental degradation and changes in farming practices, are exogenous to factors that otherwise determine emigration. Therefore, it is not necessary to explicitly control for many other social and economic factors that also affect emigration. Statistical identification comes from the considerable climate variability within Mexican states that occurred in the two 5-y periods under study: 1995 to 2000 and 2000 to 2005. During this decade, many Mexican states became drier or hotter while other states became wetter or colder. Unfortunately, data for periods early than 1995 are not sufficiently reliable to include in our analysis (*SI Appendix, part 2*).

We use the estimated sensitivity of migration to climate change to project emigration responses to a potential range of future climate trends. Such a method implicitly assumes that the response to changes in the climate variables is linear and symmetric, and that migration responses to 5-y changes in climate conditions can be applied to longer run trends. We acknowledge that, in actuality, the response to a trend may differ from the response to periodic variability, and adaptations not taken in response to short-term (annual or decadal) variability may be implemented under a sustained trend. For example, if farmers become convinced that unfavorable climatic conditions will be sustained indefinitely, they have more of an incentive to invest in irrigation and other infrastructure that would mitigate the effects of the unfavorable conditions than if they expect the conditions to be temporary in nature. For the population studied here, however, we believe that options for mitigating unfavorable climate conditions are limited by a lack of capital for significant investments in infrastructure.

## Results

### Estimation of Semielasticity of Emigration with Respect to Crop Yields.

We estimate a two-stage model of the following form:

$$Y_{it} = \alpha + \beta A_{it} + g_t + f_i + \varepsilon_{it} \quad [1]$$

and

$$A_{it} = \delta + \gamma Z_{it} + h_t + k_i + \mu_{it} \quad [2]$$

where  $i$  indicates a Mexican state and  $t$  indicates the time period. In Eq. 1,  $Y_{it}$  is the percent of the population in state  $i$  at the beginning of period  $t$  that migrated abroad during the period.  $A_{it}$  is the log of crop yield (either corn or corn plus wheat) in state  $i$  and period  $t$ . The parameter of interest is  $\beta$ , which gives the semielasticity of international migration with respect to crop yield.  $g_t$  captures the aggregate time effect in period  $t$  that is common

among all states, such as the effect of NAFTA, the Peso crisis, and changes in US border controls such as increased border enforcement after 2001. A set of unrestricted state dummy variables, represented by  $f_i$ , are included to capture time-invariant state factors, such as tradition to migrate and distance to the United States; models with state dummies are referred to as “fixed-effects” models. Because our sample consists of two periods, including state dummy variables is equivalent to examining the effects of changes in the variables over the periods (i.e., first differencing the data).  $\varepsilon_{it}$  is an error term that includes all other time-varying and state-specific factors that influence emigration.

Because  $\varepsilon_{it}$  may be correlated with  $A_{it}$ , we estimate the model by fixed-effects two-stage least-squares (FE-TSLS) and fixed-effects limited-information maximum-likelihood (FE-LIML). Identification in these models arises from climate measures, indicated by the vector  $Z_{it}$  in Eq. 2, used as instrumental variables for crop yields. (And with state fixed effects  $f_i$  and  $k_i$  in the first- and second-stage equations, the model exploits changes in climate.) Because climatic changes are likely to be uncorrelated with factors that influence migration apart through their effect on crop yields, FE-TSLS and FE-LIML should provide consistent estimates of  $\beta$  (35, 36). Intuitively, only variations in crop yields that are associated with changes in climate are used to estimate the effect of crop yields on out-migration in these models.

For comparison purposes, we also estimate the emigration model using ordinary least-squares excluding state dummies (i.e., pooled OLS), random effects (RE), and fixed effects (FE).

Table 1 presents our main estimates of  $\beta$ , the responsiveness of emigration to crop yields. In the top panel, the independent variable is the natural log of corn yield. Note that pooled OLS and RE estimates do not have the expected sign and are statistically insignificant. The FE estimate has the expected sign and is significant, but is substantially lower in magnitude than FE-TSLS and FE-LIML, suggesting a bias toward zero. For both FE-TSLS and FE-LIML, we use annual precipitation, annual average temperature, and summer temperature (as the main growing season for corn in Mexico includes May, June, and July) as exogenous instruments. Quadratic terms are included because previous research has found nonlinear relationships between climate measures and crop yields (37). The first stage regression results (*SI Appendix, part 3*) suggest that those climate variables are highly correlated with corn yields and the estimated coefficients make physiological sense (25, 37). Based on the FE-TSLS estimate, a 10% decrease in corn yields would increase the fraction of the population emigrating by 2.11 percentage points. FE-LIML gives a quantitatively similar estimate (−2.25%). Both estimates are highly statistically significant (with

**Table 1. Estimated effect of crop yields on emigration ( $\beta$ )**

Yield statistic	Pooled OLS	RE	FE	FE-TSLS	FE-LIML
<b>Corn</b>					
Log of crop yields	0.005 (0.008)	0.003 (0.009)	−0.117 <sup>†</sup> (0.026)	−0.211 <sup>†</sup> (0.036)	−0.225 <sup>†</sup> (0.042)
State dummies	No	No	Yes	Yes	Yes
F-statistic*	—	—	—	5.5	5.5
P value	—	—	—	0.0009	0.0009
Adjusted R <sup>2</sup>	0.0115	0.0115	0.6775	0.5897	0.5619
<b>Corn plus wheat</b>					
Log of crop yields	0.006 (0.008)	0.005 (0.009)	−0.113 <sup>†</sup> (0.031)	−0.183 <sup>†</sup> (0.036)	−0.214 <sup>†</sup> (0.051)
State dummies	No	No	Yes	Yes	Yes
F-statistic*	—	—	—	9.2	9.2
P value	—	—	—	0.0000	0.0000
Adjusted R <sup>2</sup>	0.0139	0.0139	0.6490	0.6076	0.5622

Sample size is 64 for all regressions. Numbers reported in parentheses are robust SEs that allow for possible heteroscedasticity.

\*F-statistic for instruments in first-stage equation.

<sup>†</sup>Significant at 1% level.

t statistics >5) and close to each other, which suggests that possible biases from small sample and weak instruments are relatively minor (*SI Appendix, part 3*, provides more details on reduced-form estimates and first stage regressions).

The lower part of Table 1 presents results for the combined yield of corn and wheat, whereby wheat production is transformed into equivalent corn production based on the value of total output, using ratios of national average prices. The results are quite similar to those in the upper panel (*SI Appendix, part 3*, shows first-stage regression results). The FE-TSLS and FE-LIML estimates are  $-0.183$  and  $-0.214$ , respectively, and both are significant at the 1% level. Therefore, the semielasticity of emigration with respect to crop yields does not seem to be particularly sensitive to the choice of crop type.

**Robustness Checks.** We perform several robustness checks in Table 2. First, to assess the possible impact of outlying or unusual observations in our data on the main results reported in Table 1, we perform two tests. In part A of Table 2, we drop the Mexican states with negative emigration ratios and rerun the regressions. Such observations arise from errors in using a residual approach to estimate out-migration flows, causing certain states to have negative emigration ratios for the latter period of 2000 to 2005. For corn, the estimated coefficient is  $-0.192$  and  $-0.235$  using FE-TSLS and FE-LIML, respectively. For corn and wheat combined, the coefficients are  $-0.141$  and  $-0.182$  using FE-TSLS and FE-LIML, which are somewhat smaller in magnitude than—but nonetheless similar to—the cases in which all states are included. We have also dropped two states with the greatest decreases in annual mean temperature and summer mean temperature between the two periods: Michoacán and Nuevo León (Table 2, part B). For corn, the estimated coefficient is  $-0.222$  and  $-0.241$  using FE-TSLS and FE-LIML, respectively. For corn and wheat combined, the coefficients are  $-0.225$  and  $-0.269$  with FE-TSLS and FE-LIML, respectively. These estimates are also highly statistically significant.

We next examine possible effects of weak instruments in our regressions. It is well known in the econometrics literature that the use of fewer instruments reduces possible weak instrument

bias. In part C of Table 2, we use only precipitation and its square as IV and rerun FE-TSLS and FE-LIML. Similarly, part D of Table 2 reports results that take into account only annual mean temperature and summer mean temperature and their squares as instruments in the  $Z_{it}$  vector. Overall, the results are quite similar to those in Table 1. Also, the results do not vary much based on the use of FE-TSLS or FE-LIML.

Third, we examine possible effects of correlation between the error term and the instruments. Note that FE-TSLS and FE-LIML estimates would be biased if the error term  $\varepsilon_{it}$  contains a component that is correlated with climate variables. For example, if people’s preference to live in cooler places increases as temperatures rise, then we would expect emigration to increase even without crop yield changes. If another channel through which climate might affect emigration operates in the same direction as through crop yields changes, we would expect our estimates to be upwardly biased in absolute value.

One way to assess the magnitude of such biases is to focus our analysis on more rural areas of the country, in which the crop yield/migration linkage would be expected to be substantially more important. In part E of Table 2, we estimate the model for the 16 states with at least 25% of their population living in rural areas. Despite the smaller sample, the SEs are much smaller than those in Table 1, suggesting a lower noise-to-signal ratio. In addition, the estimated semielasticities are not very different from those of the original sample. Based on FE-TSLS specification, the semielasticity figures estimated from the full sample are  $-0.211$  for corn and  $-0.183$  for corn and wheat combined, and  $-0.157$  for corn and  $-0.182$  for corn and wheat combined based on rural states. Thus the possible magnitude of bias seems limited.

Last, we investigate whether our main results are driven by states that border the United States, which could be quite different from the rest of Mexico in terms of emigration. Specifically, because of the concentration of foreign-owned factories (“maquiladoras”) in border states in the pre-NAFTA era, the introduction of NAFTA in the mid-1990s could have affected those states less than other areas of Mexico in terms of emigration. The relationship between

**Table 2. Robustness checks for estimate of  $\beta$**

Check	Corn	Corn plus wheat
A: Dropping observations with negative emigration ratios		
FE-TSLS	$-0.192^*$ (0.040)	$-0.141^*$ (0.034)
FE-LIML	$-0.235^*$ (0.066)	$-0.182^*$ (0.081)
B: Dropping outlying observations judged by interperiod temperature changes		
FE-TSLS	$-0.222^*$ (0.047)	$-0.225^*$ (0.052)
FE-LIML	$-0.241^*$ (0.057)	$-0.269^*$ (0.075)
C: Using only precipitation as instrumental variable		
FE-TSLS	$-0.230^*$ (0.064)	$-0.261^*$ (0.081)
FE-LIML	$-0.236^*$ (0.069)	$-0.267^*$ (0.086)
D: Using only temperature variables as instrumental variable		
FE-TSLS	$-0.209^*$ (0.034)	$-0.185^*$ (0.036)
FE-LIML	$-0.215^*$ (0.036)	$-0.204^*$ (0.045)
E: Using only rural states (rural population >25%)		
FE-TSLS	$-0.157^*$ (0.010)	$-0.182^*$ (0.015)
FE-LIML	$-0.166^*$ (0.013)	$-0.194^*$ (0.019)
F: Dropping border states		
FE-TSLS	$-0.215^*$ (0.035)	$-0.253^*$ (0.048)
FE-LIML	$-0.237^*$ (0.044)	$-0.282^*$ (0.060)

The dependent variable is the percent of the population in each state that emigrated in the 1995–2000 or 2000–2005 period. Numbers reported in parentheses are robust SEs. State dummies are included in all regressions. Sample sizes are 56 for A, 60 for B, 64 for C and D, 32 for E, and 52 for F. In D, the 16 Mexican states that have more than 25% of their population living in rural areas are Campeche, Chiapas, Durango, Guanajuato, Guerrero, Hidalgo, Michoacán, Nayarit, Oaxaca, Puebla, Querétaro, San Luis Potosí, Sinaloa, Tabasco, Veracruz, and Zacatecas. The border states excluded in F are Baja California, Chihuahua, Coahuila, Nuevo León, Sonora, and Tamaulipas.

\*Significant at 1% level.



crop yields and migration could also be different in border states because of their proximity to the United States. In part F of Table 2, we exclude the six border states of Mexico. The estimated semielasticities became even larger in magnitudes and remain highly significant.

**Forecasting Future Mexican Emigration Under Climate Change.** Our estimate of the elasticity of migration is conditional on many factors specific to Mexico for the period under study, such as the macroeconomic situation compared with that of the United States, the population share of youths (who are more likely to migrate), farming practices, the relative importance of the agricultural sector, and agricultural policies including responses to droughts and other climatic events that adversely affect crop yields (16). For example, if government policies intended to help subsistence farmers become more effective, or changes in farming practices allow farmers to be more resilient to adverse climatic conditions, the estimated yield/emigration sensitivity may become smaller as well (16, 32). Changes in US immigration policies and border enforcement could also substantially alter the Mexico crop yield/emigration relationship (27, 29, 30).

Keeping these idiosyncratic factors in mind, it is nevertheless instructive to predict future migrant flows for Mexico using the estimates at hand to assess the possible magnitude of climate change-related emigration (Table 3). Our projection exercise does not depend on whether past climate variability in Mexico was caused by greenhouse gas emissions, as long as the migration responses are similar to those that would occur in response to anthropogenic climatic changes.

Specifically, we project the emigration rate of the adult Mexican population (aged 15–65 y) resulting from the predicted changes in crop yields from Rosenzweig and Iglesias (ref. 38; see also [http://sedac.ciesin.columbia.edu/giss\\_crop\\_study/index.html](http://sedac.ciesin.columbia.edu/giss_crop_study/index.html))

and Cline (23) at approximately year 2080. We use  $-0.2$  as the semielasticity of emigration with respect to crop yields.

The first three panels of Table 3 are based on scenarios and crop yield predictions made by Rosenzweig and Iglesias (38), all assuming an eventual stabilization level of atmospheric CO<sub>2</sub> concentration of 555 ppm, which, under the relatively conservative scenario B1 of the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (1), approximately corresponds to the year 2080 and represents global mean temperature increase of 1 °C to 3 °C above recent temperatures. The three panels use climate forecasts from different General Circulation Models (GCMs), including those of the Goddard Institute for Space Studies, the Geophysical Fluid Dynamics Laboratory (GFDL), and the United Kingdom Meteorological Office (UKMO). Although, in all cases, Mexico is expected to experience some reductions in crop yields as a result of climate change, the magnitude depends to a large extent on whether the fertilization effect of CO<sub>2</sub> is included and whether active agricultural adaptation measures are taken. On the one extreme with no CO<sub>2</sub> fertilization effect and no adaption, crop yields in Mexico are predicted to decline by at least 39% (GFDL), or as much as 48% (UKMO). In that case, the increase in Mexico's emigration as a share of population (i.e., the fraction of all Mexican-born people living abroad) would be between 7.8% and 9.6%. Mexico's population will differ in the future and the elasticity may change if the rural population fraction decreases further, and if the agricultural sector itself changes (i.e., results are sensitive to implicit assumptions about the path of development). Nevertheless, to indicate the broad scope of the phenomenon, we convert these percentages to absolute numbers of emigrants. Using today's population of 70 million as the base for the age 15–65 y population in Mexico, this percentage increase corresponds to an additional 5.5 to 6.7 million emigrants.

**Table 3. Forecast of future Mexican emigration at the national level under different climate scenarios**

Scenario		Change in crop yields, %	Change in emigrants as percent of population, %	Change in no. of adult emigrants, millions <sup>†</sup>
CO <sub>2</sub> effect	Adaptation*			
Rosenzweig and Iglesias (38): GISS <sup>‡</sup>				
No	No	-46	9.2	6.4
Yes	No	-35	7.0	4.9
Yes	Level 1	-27	5.4	3.8
Yes	Level 2	-13	2.6	1.8
Rosenzweig and Iglesias (38): GFDL <sup>‡</sup>				
No	No	-39	7.8	5.5
Yes	No	-28	5.6	3.9
Yes	Level 1	-20	4.0	2.8
Yes	Level 2	-10	2.0	1.4
Rosenzweig and Iglesias (38): UKMO <sup>‡</sup>				
No	No	-48	9.6	6.7
Yes	No	-37	7.4	5.2
Yes	Level 1	-31	6.2	4.3
Yes	Level 2	-15	3.0	2.1
Cline preferred estimates <sup>§</sup>				
No	Not Clear	-35	7.1	5.0
Yes	Not Clear	-26	5.1	3.6

\*Level 1 adaptation includes changes that imply small additional cost to the farmers and not necessary policy changes, such as shifts in planting dates, variety and crop, and increases in water application to irrigated crops. Level 2 adaptation includes higher order adaptations that imply significant additional costs to the farmers, such as large shifts in crop production timing, increased fertilizer application, installation of irrigation systems, development of new varieties, and/or changes in policy.

<sup>†</sup>Assuming that the population aged 15–65 y is 70 million in Mexico.

<sup>‡</sup>The equilibrium scenarios for three major General Circulation Models were used by Rosenzweig and Iglesias (38): the Goddard Institute for Space Studies (GISS), the GFDL, and the UKMO.

<sup>§</sup>The Cline estimates (23) give equal weights to estimates from Mendelsohn-Schlesinger Ricardian model and Rosenzweig and Iglesias (38) crop model. Both assume some levels of adaptation.

The actual effect of CO<sub>2</sub> on crop yields remains very uncertain (39). If CO<sub>2</sub> fertilization effects are taken into account and major (i.e., level 2) adaptation measures are taken, there would be only a modest (10–15%) decline in crop yields. In that case, our model predicts that 2% to 3% of Mexicans (or 1.4–2.1 million) would migrate to other countries (mostly to the United States if current conditions persist) because of the climate-driven decline in crop yield.

The last panel of Table 3 presents results based on predictions made by Cline (23), which basically combine estimates from the Rosenzweig and Iglesias crop model and the Mendelsohn-Schlesinger Ricardian statistical model. The Cline estimates use year 2080 as a reference point but are approximately comparable with the 555 ppm CO<sub>2</sub> concentration level used by Rosenzweig and Iglesias (38), and have incorporated a moderate level of adaptation. In this scenario, crop yield in Mexico is expected to decline by 35% without CO<sub>2</sub> effects and by 26% with CO<sub>2</sub> effects, which we forecast would lead 7.1% and 5.1% of the population (or 5.0 and 3.6 million people) to emigrate, respectively.

The median of the forecasted increase in the share of the population expected to emigrate in Table 3 is approximately 6%, which implies that 4.2 million additional adult Mexicans would emigrate as a result of climate change induced crop yields reductions with today's population as the base. It is important to note that our projections should be interpreted in a *ceteris paribus* manner, as many other factors besides climate could potentially influence migration from Mexico to the United States. Demographic changes are especially important in shaping future migration flows. Hanson and McIntosh (26), for example, predict that Mexico will send fewer migrants in the next several decades as a result of a decline in fertility. Our projections are informative, nevertheless, in quantifying the potential magnitude of impacts of climate change on out-migration.

## Discussion

To conclude, we have examined the link between climate-driven productivity changes in the agricultural sector and out-migration with Mexico used as an example. Our results are conservative in at least two respects. First, projected changes in crop yields are considerably larger than those observed in our data. If crop yield affects emigration in a nonlinear fashion, our linear specification would likely underestimate the full impact of climate on crop yields in the future. Second, as we focus on only crop yields, our estimate provides a lower bound for the overall impact of climate change on emigration through agriculture, which could also be affected by changes in the total acreage of land cultivated. Even so, the estimated elasticity of emigration with respect to crop yield changes is statistically significant and large in a practical sense. This suggests that crop yield-induced migration will be a significant issue in many areas of the world that are expected to experience a substantial reduction in yields as a result of climate change, including much of Africa, India, Bangladesh, Latin America, and Australia, among others. Because climate change

may induce out-migration through channels not examined in this study, the overall effect may be larger, particularly if atmospheric greenhouse gas concentration levels continue to increase sharply and countries fail to implement aggressive adaptation measures.

Given these projections, certain migrant-receiving countries, including the United States, are expected to face increased migration streams as a result of existing transnational networks with migrant-sending countries that are particularly vulnerable to climate change. However, some aspects of the Mexico/United States emigration situation are also unique, so extrapolation of our quantitative findings to the global level would be inappropriate. Nevertheless, application of our methods to other regions and other climate-related drivers of immigration, and to internal migration, would provide insights into potential future immigration and migration “hot spots,” as well as into the overall magnitude of the looming changes. Additional insights concerning the response of migration sensitivities to trends in climate variables (i.e., whether the semielasticity would decrease or increase in a different climate) may also be gained from study of regions with data sets extending over a longer period. Future research could also use different methods (e.g., ethnography) to complement our statistical approach to deepen our understanding of people's motives to migrate when faced with climate change.

## Materials and Methods

**Data.** We use data on emigration, crop yields, and climate for each Mexican state, all averaged over two consecutive 5-y periods of 1995 to 2000 and from 2000 to 2005 (*SI Appendix, Table S1*). The emigration data are derived from Mexican censuses of 1995, 2000, and 2005. Specifically, we use a residual approach to compute out-migration flows: we start from 5-y population changes and adjust for mortality and internal migration, then calculate percentages of people who migrated within a period among all people aged 15 to 65 y who were in Mexico at the beginning of the period. This measure thus captures relatively long-term population movements rather than more transitory ones. Because of a large number of undocumented Mexican emigrants to the United States (40), all methods aimed at accurately determining emigration rates entail considerable uncertainty. Our method provides the best available estimates of state-level emigration rates, and matches other studies in terms of national totals (40).

To measure crop yields, we focus on corn, because it is the principal food stock of the Mexican diet and the most important crop. Corn accounts for 60% of land under cultivation and agricultural output by value, and provides the main source of livelihood to 40% of people working in agriculture (32). We also examine an alternative measure that combines corn and wheat, as wheat is a major substitute crop for corn and is also widely cultivated in Mexico (41). Yearly information for corn and wheat production and areas of land planted for each state were obtained from the Mexican Ministry of Agriculture, from which we calculate 5-y average crop yields. Our state-level climate data on annual precipitation, annual mean temperature, and summer mean temperature were obtained from the Mexican National Weather Service (*SI Appendix, part 2*, provides further description).

**ACKNOWLEDGMENTS.** We thank Douglas Massey, Cynthia Rosenzweig, Sam Schulhofer-Wohl, seminar participants at the Russell Sage Foundation, and two anonymous referees for invaluable comments. The views expressed in the article do not necessarily represent those of the US government.

- Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: The Physical Science Basis* (Cambridge Univ Press, Cambridge, UK).
- Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability* (Cambridge Univ Press, Cambridge, UK).
- Ayres R, Walter J (1991) The greenhouse effect: Damages, costs and abatement. *Environ Resour Econ* 1:237–270.
- Martin P, Lefebvre M (1995) Malaria and Climate—sensitivity of malaria potential transmission to climate. *Ambio* 24:200–207.
- Myers N, Kent J (1994) *Environmental Exodus: An Emergent Crisis in the Global Arena* (Climate Institute, Washington, DC).
- McLeman R, Smit B (2006) Migration as an adaptation to climate change. *Clim Change* 76:31–53.
- Stern N, et al. (2007) *The Stern Review of the Economics of Climate Change* (Cambridge Univ Press, Cambridge).
- Warner K, et al. (2009) *In Search of Shelter: Mapping the Effects of Climate Change on Human Migration and Displacement* (United Nations University, CARE, and CIESIN-Columbia University and in close collaboration with the European Commission “Environmental Change and Forced Migration Scenarios Project”, the UNHCR, and the World Bank, Bonn, Germany).
- Myers N (2002) Environmental refugees: A growing phenomenon of the 21st century. *Philos Trans R Soc Lond B Biol Sci* 357:609–613.
- World Bank Group (2008) *World Development Report 2009: Reshaping Economic Geography* (The World Bank Group, Washington, DC).
- De Haas H (2009) *Mobility and Human Development* (United Nations Development Programme, Washington, DC).
- Stark O, Levhari D (1982) On migration and risk in LDCs. *Econ Dev Cult Change* 31: 191–196.
- de Sherbinin A, et al. (2008) Rural household demographics, livelihood and the environment. *Glob Environ Change* 18:38–53.
- Gleditsch NP, Nordas R, Salehyan I (2007) *Climate Change and Conflict: The Migration Link* (International Peace Academy, New York).
- Leighton M (2009) *Migration, Environment, and Climate Change: Assessing the Evidence*, eds Lazcko F, Aghazarm C (International Organization for Migration, Geneva, Switzerland), pp 319–351.

16. Alscher S, Faist ST (2009) *Environmental Factors in Mexican Migration: The Cases of Chiapas and Tlaxcala* (UN University, New York).
17. Dóös BR (1997) Can large-scale environmental migrations be predicted? *Glob Environ Change* 7:41–61.
18. Oliver-Smith A (2009) *Nature, Society, and Population Displacement: Toward an Understanding of Environmental Migration and Social Vulnerability* (UN University Institute for Environment and Human Security, Bonn, Germany).
19. Black R (2001) *Environmental Refugees: Myth or Reality? New Issues in Refugee Research. Working Paper no. 34* (United Nations High Commissioner for Refugees, Geneva).
20. Perch-Nielsen SL, Bättig MB, Imboden D (2008) Exploring the link between climate change and migration. *Clim Change* 91:375–393.
21. Adger WN (2006) Vulnerability. *Glob Environ Change* 16:268–281.
22. World Bank Group (2009) *World Development Report 2010: Development and Climate Change* (The World Bank Group, Washington, DC).
23. Cline WR (2007) *Global Warming and Agriculture: Impact Estimates by Country* (Peterson Institute for International Economics, Washington, DC).
24. Rosenzweig C, Parry ML (1994) Potential impact of climate change on world food supply. *Nature* 367:133–138.
25. Schlenker W, Hanemann WM, Fisher AC (2005) Will U.S. agriculture really benefit from global warming? Accounting for irrigation in the Hedonic approach. *Am Econ Rev* 95:395–406.
26. Hanson GH, McIntosh C (2009) The demography of Mexican migration to the US. *Am Econ Rev* 99:22–27.
27. Hanson GH, Spilimbergo A (1999) Illegal immigration, border enforcement and relative wages: Evidence from apprehensions at the U.S.-Mexico border. *Am Econ Rev* 89:1337–1357.
28. Orrenius PM, Zavodny M (2005) Self-selection among undocumented immigrants from Mexico. *J Dev Econ* 78:215–240.
29. Reyes BI (2004) Changes in trip duration for Mexican immigrants to the United States. *Popul Res Policy Rev* 23:235–257.
30. Fernandez-Kelly P, Massey DS (2007) Borders for whom? The role of NAFTA in Mexico-U.S. migration. *Ann Am Acad Polit Sci* 610:8–118.
31. Munshi K (2003) Networks in the modern economy: Mexican migrants in the U.S. labor market. *Q J Econ* 118:549–599.
32. Nadal A (2000) *The Environmental and Social Impacts of Economic Liberalization on Corn Production in Mexico* (Oxfam GB and WWF International, Gland, Switzerland).
33. Schwartz ML, Notini J (1994) *Desertification and Migration* (U.S. Commission on Immigration Reform, Mexico and the United States, Washington, DC).
34. Stahle DW, et al. (2009) Early 21<sup>st</sup>-century droughts in Mexico. *EOS* 90:89–90.
35. Angrist JD, Pischke J (2008) *Mostly Harmless Econometrics: An Empiricist's Companion* (Princeton Univ Press, Princeton, NJ).
36. Stock JH, Yogo M (2005) *Identification and Inference for Econometric Models: Essays in Honor of Thomas J. Rothenberg*, eds Stock JH, Andrews DWK (Cambridge Univ Press, Cambridge, UK).
37. Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proc Natl Acad Sci USA* 106:15594–15598.
38. Rosenzweig C, Iglesias A (2006) *Potential Impacts of Climate Change on World Food Supply: Data Sets from a Major Crop Modeling Study* (Goddard Institute for Space Studies, Columbia University, New York).
39. Long SP, Ainsworth EA, Leakey AD, Nösberger J, Ort DR (2006) Food for thought: lower-than-expected crop yield stimulation with rising CO<sub>2</sub> concentrations. *Science* 312:1918–1921.
40. Passel JS, Pew Research Center (2006) *The Size and Characteristics of the Unauthorized Migrant Population in the U.S. – Estimates Based on the March 2005 Current Population Survey* (Pew Hispanic Center, Washington, DC).
41. US Department of Agriculture (1994) *Major World Crop Areas and Climatic Profiles. Agricultural Handbook no. 664* (US Department of Agriculture, Washington, DC).