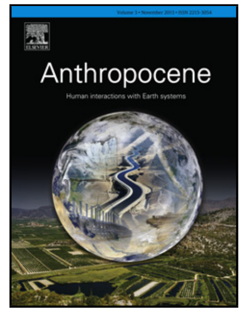


Title: Agricultural change and resilience: Agricultural policy, climate trends and market integration in the Mexican maize system

Authors: Hallie Eakin, Stuart Sweeney, Amy M. Lerner, Kirsten Appendini, Hugo Perales, Doug Steigerwald, Candida F. Dewes, Frank Davenport, Julia C. Bausch

| | |
|---|---|
| PII: | S2213-3054(18)30038-9 |
| DOI: | https://doi.org/10.1016/j.ancene.2018.08.002 |
| Reference: | ANCENE 178 |

To appear in:

| | |
|---|---|
| Received date: | 22-1-2018 |
| Revised date: | 1-8-2018 |
| Accepted date: | 2-8-2018 |

Please cite this article as: Eakin H, Sweeney S, Lerner AM, Appendini K, Perales H, Steigerwald D, Dewes CF, Davenport F, Bausch JC, Agricultural change and resilience: Agricultural policy, climate trends and market integration in the Mexican maize system, *Anthropocene* (2018), https://doi.org/10.1016/j.ancene.2018.08.002

Full Title: Agricultural change and resilience: Agricultural policy, climate trends and market integration in the Mexican maize system

Short Title: Agricultural change and resilience in Mexico

Authors: Eakin, Hallie[a,1]; Sweeney, Stuart[b]; Lerner, Amy M.[c]; Appendini, Kirsten[d]; Perales, Hugo[e]; Steigerwald, Doug[f]; Dewes, Candida F.[g]; Davenport, Frank[h]; Julia C. Bausch[i].

[1]Author to whom correspondence should be addressed (hallie.eakin@asu.edu)

[a] School of Sustainability, Arizona State University, 800 S Cady Mall, Tempe, Arizona 85287-5502, Hallie.eakin@asu.edu, (480)727-7764

[b] Department of Geography, University of California, Santa Barbara, CA 93106-4060

[c] Laboratorio Nacional de Ciencias de la Sostentabilidad, Instituto de Ecologia, Universidad Nacional Autónoma de México, Ciudad Universitaria, Ciudad de México, Mexico.

[d] Centro de Estudios Demográficos, Urbanos y Ambientales (CEDUA), El Colegio de México, Carr. Picacho-Ajusco 20, Fuentes del Pedregal, Tlalpan, 010740, Ciudad de México, D.F

[e] El Colegio de la Frontera Sur, San Cristóbal, Chiapas, México 29290

[f] Department of Economics, University of California, Santa Barbara, CA 93106

[g] Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder and Physical Sciences Division, NOAA/ESRL, 325 Broadway, Boulder, CO 80305

[h] Climate Hazards Center, Department of Geography, University of California, Santa Barbara, CA 93106

[i] Kyl Center for Water Policy, Morrison Institute of Public Policy, Arizona State University, Phoenix, AZ 85004

**Highlights:**

- This paper provides a systemic, multi-scalar investigation of the drivers and outcomes of the Mexican maize system in face of environmental, social and economic uncertainty.
- Domestic policy reforms, rather than climatic factors or international market dynamics, have been primary drivers of change.
- Maize persistence, despite a lack of market incentives, underscores its multifunctional nature and role in domestic food security, and the need for domestic policy to reflect these functions.
- Results highlight the influence of domestic policy, in addition to exogenous global stressors, in the resilience of the maize system.

**Abstract**

Ensuring that national food systems have capacity to withstand volatility and shocks is a growing concern. Given the complex processes involved, multi-scalar, multi-stressor analyses of critical food systems are needed. This paper presents a multi-scalar analysis of the Mexican maize system to provide insight into the sector's evolution. The literature suggests that, over the last 30 years, climate trends, domestic and international market dynamics, and domestic policy changes have affected Mexico's maize sector. In contrast, this study finds no conclusive evidence of wide-spread abandonment of maize. In addition, while economic globalization and climatic changes are often presented as the primary drivers of change in Mexico's maize sector, results of this study show that domestic policy has been equally, if not more, influential in the sector's evolution. More than international market integration, the relatively recent geographic concentration of commercial supplies within Mexico has increased national sensitivity to idiosyncratic shocks affecting the dominant supply region. In this light, smallholder persistence across Mexico may represent an underutilized strategic asset in policy efforts to enhance both domestic food security and national-level resilience. The Mexican case illustrates the potential role for proactive domestic policy in shaping sensitivities in the national food system to both internal and exogenous shocks.

**Keywords**: food security, livelihoods, globalization, climate trends, Mexico

## 1. Introduction

In the face of increased farm consolidation, economic integration, and urbanization, the viability of smallholders has long been debated (Akram-Lodi and Kay, 2010). Most of the world's farms are small (<2 ha), and these farmers are often considered particularly vulnerable to emerging processes of environmental change and economic globalization and also individually resilient to exogenous stress (Dasgupta et al., 2014). For example, while smallholders often are characterized as lacking the capital, access to institutional services, and technology needed to effectively reduce their vulnerability to climatic shocks and to take advantage of economic opportunities, many smallholders have developed diverse coping mechanisms (i.e., risk pooling, crop diversification, livelihood diversification) that permit their survival, albeit often in states of chronic poverty (Eakin et al., 2014c). Smallholder farming has thus been surprisingly persistent (Rigg et al., 2016), raising questions concerning the role of smallholders in national and international food system dynamics.

The Mexican maize system—historically characterized by a large "peasant" (*campesino*) population, as well as a vibrant commercial agricultural sector—presents a valuable case for evaluating the response of food systems to both internal and external shocks at different scales of analysis and the role of smallholders in such responses. Food systems are complex, dynamic, coupled social-ecological systems. They encompass not only the activities essential for food provisioning (from production to waste management) but also broad-scale and local-level social and biophysical drivers of system change (e.g., climate change, demographic shifts), and diverse outcomes: food security, ecological integrity, and social welfare (Ericksen, 2008).

Given Mexico's demand for maize in international markets, the Mexican maize system is of international interest. With an average daily per capita consumption of approximately 267 g (Ranum et al., 2014), maize is fundamental to Mexico's food security. Significant shifts in national policy and trade, together with climatic trends, have raised concerns about the future of maize in Mexico, despite its iconic status. The current international negotiation of the continuation of the North American Free Trade Agreement (NAFTA) in the United States, Canada, and Mexico has once again put maize, land use, and livelihoods into the center of politics (see for example, Semple, 2017).

Mexico's maize sector epitomizes the complex interaction of trade, climatic variability, and politics in rural life. In the late 1980s and 1990s, alarm over the future of Mexico's maize economy escalated, and today the popular press often presents the maize sector as having all but collapsed (see, for example, Carlsen, 2013). Scholars have associated shifts in trade, agrarian policy, and climatic changes with environmentally-induced migration and the growth of illicit economies (Dube et al., 2014; Feng et al., 2010). This narrative of collapse is shaped by two assumptions. First, that the cultural and social foundation of maize farming—the smallholder sector—was decimated by market liberalization in general and NAFTA in particular (Wise, 2009) and second, that climate change and extremes are increasingly making rain-fed production unviable (Monterroso Rivas et al., 2010).

This literature provides the basis for several hypotheses. First, given the sensitivity of maize crops to climatic stress, we would expect to see the effect of climatic stress on maize yield trends. Second, we would anticipate that over the last 30 years, much of the land area in maize would have been abandoned, as climatic stress and increased market competition are presumed to have driven farmers off the land, into the cities, and across the U.S. border (Carton de Grammont, 2009; Feng et al., 2010). Case study research, for example, suggests that maize imports have displaced domestic production (González Alvarado, 2012), maize fields have been replaced by forests or houses (Klooster, 2003; Lerner et al., 2013), and non-farm livelihoods—including involvement in the illicit drug trade—are now more viable options in the rural sector (de Janvry and Sadoulet, 2001; Dube et al., 2014; Eakin and Appendini, 2008). Finally, we would anticipate that market liberalization—embodied by the implementation of NAFTA—would have resulted in greater integration of U.S. and Mexican maize markets, potentially increasing the sensitivity of the sector to external environmental and economic shocks stemming from increased interdependency with the U.S. policy and environmental context (Wise, 2009; Fitting, 2006).

Nevertheless, the findings of individual case studies may not provide an accurate picture of the overall state of the maize system, bounded at the national scale, and the factors that drive its dynamics: multi-scalar analyses are required. Vulnerability research, for example, has demonstrated that processes that have strong explanatory power at one spatial scale can be muted at other scales (O'Brien et al., 2004b) and that households' adaptive strategies can collectively affect broader systems dynamics in ways that ultimately undermine local vulnerability mitigation efforts (Eakin and Wehbe, 2009). Studies that have applied the concept of "double exposure" (O'Brien and Leichenko, 2000) have repeatedly demonstrated that the impacts of global processes are filtered by institutional, socio-cultural, and environmental conditions at different scales (Manuel-Navarrete et al., 2011; O'Brien et al., 2004a; Silva et al., 2010). The hegemonic presence of globalization and climate change in current global change discourse, however, can bias interpretation against the role of local- and regional-level processes that can mediate or amplify the influence of global change processes. For these reasons, there is a need for empirical research that systemically evaluates the sector's sensitivity to the combined stressors of climatic, market integration, and policy change at different scales of analysis.

This study uses a multi-scalar, interdisciplinary approach to explore the interaction of global change processes, represented as market integration and climatic trends, with national- and regional-level processes such as demographic shifts and changes in policy priorities in order to assess the current state of maize production in Mexico in relation to market shocks and climatic stress. We evaluated the evolution of the sector's sensitivity to market integration, associated domestic policy changes, and trends in climatic parameters over the period from 1980 to 2014. Of particular interest is the role of rain-fed smallholder farms in national maize sector dynamics and national-level vulnerability. The vulnerability of the maize system is a function of the exposure and sensitivity of the system to economic and climatic shocks, both regionally and nationally, and the system's ability to buffer and recover from such shocks over time, in terms of maintaining maize production (supply, regional distribution) and price stability. To explore evidence of the sector's sensitivity to these stressors, we ask three questions. What is the evidence of maize sector sensitivity to climatic and market stress? What evidence is there that markets have become more integrated, and what is the association of market integration with sensitivity to external and internal shocks? And finally, at the national scale, what has been the role of domestic policy in the maize system's evolving vulnerability? We expected to find evidence of maize abandonment in the post-liberalization period, consistent with economic projections of the impact of NAFTA and Mexico's domestic policy trends, exacerbated by the stress of climatic variability. Given the heterogeneity of Mexico's maize sector and agroclimatic landscape, however, we anticipated that the effects would be far from uniform.

## 2. Maize Farming in Mexico

Maize is produced in Mexico under highly variable conditions. Most maize produced is the culturally preferred white maize used in domestic cuisine and commercial tortilla and maize flour manufacturing. Yellow maize—the type most commonly produced in the U.S.—is considered inferior for human consumption and is primarily produced for the livestock market (Appendini, 2014). Farmers in central and southern Mexico plant traditional varieties of white maize in large part because they are robust to local agro-climatic conditions (Mercer et al., 2012). Farm scale and market orientation also vary widely, from subsistence and semi-subsistence production on small rain-fed parcels to large-scale commercial (irrigated) operations that can reach sizes of several hundred hectares (Eakin et al., 2014b). The most recent agricultural census data indicate a slight increase in maize producers from 2.75 million in 1991 to 2.83 million in 2007 (Instituto Nacional de Estadística y Geografía (INEGI), 2007). Nationally, large-scale producers (>20 ha) constitute only 1.2% of maize producers, although collectively they are now responsible for 25.5% of production (Eakin et al., 2014b). Smallholders with less than 5 ha still represent the majority—83.2%—of producers in Mexico, farming over half the planted area and accounting for more than one-third of total maize produced (Eakin et al., 2014b).

Although government policy in the 20th century was often ambivalent about the contributions of medium- and small-scale (*ejidatarios*[†]) maize farmers to the economy, these farmers were politically and culturally important (Appendini, 2001). In the 1970s and 1980s, smallholders (<10 ha) received subsidized credit,

[†] Ejidatarios are smallholders that have *ejido* plots, or land that was redistributed to smallholders after the Mexican Revolution (1910-1917). Until 1992 when agrarian tenure laws were reformed (Article 27 of the Constitution), ejido land was organized under collective management and formal sale was prohibited. After 1992, ejidatarios could obtain individual land titles and engage in formal land markets.

insurance, and farm inputs and benefited from producer price controls and a guaranteed market for maize grain through sales to Compañía Nacional de Subsistencias Populares (CONASUPO), the federal grain marketing agency. As part of the implementation of NAFTA, beginning in 1994, the government dismantled many of these public agencies and institutions, closing CONASUPO in 1999 (Appendini, 2014). The new focus was on farmers who were considered to have market potential: typically, those with larger land holdings and access to commercial markets and irrigation (Appendini, 2014). Some scholars believe that the resulting increase in competition has led to the decline of smallholder viability (Carton de Grammont, 2009). Indeed, NAFTA and the domestic agricultural reforms that accompanied it are heralded as marking a turning point for smallholder maize farmers (de Janvry et al., 1995; Wise, 2009). The channeling of public production support to more commercial farmers, along with the liberalization of the maize sector, has led to fears that smallholders are being forced to stop growing maize (abandonment) and find alternative livelihoods (Carton de Grammont, 2009).

In parallel, concern has increased over the ability of maize farmers at all scales to adapt to climatic variability and trends. In the future, rising temperatures, increased evapotranspiration, and diminished rainfall are expected to reduce the area suitable for maize production and to suppress yields (Monterroso Rivas et al., 2010). Analyses indicate that increasing days of extreme heat (Gourdji et al., 2013) and regional trends in total precipitation and average temperature are already likely to have diminished yields in maize-producing areas of Mexico, although some of this decrease may have been offset with technological improvements (Lobell et al., 2011; Lobell et al., 2005). Maize farming in rain-fed central and southern Mexico, where smallholders predominate and cultivation of maize landraces is most pronounced, is considered most vulnerable to climatic stress (Mercer et al., 2012; Monterroso Rivas et al., 2010).

At the national scale, increased competition and global market integration can provide aggregate welfare benefits, particularly to urban consumers, and may mitigate shocks to domestic production. Thus, given adequate food distribution networks, as markets "thicken" (increased connectivity to sub-national and international maize markets), welfare effects of idiosyncratic disruptions to production caused by extreme weather events, input cost spikes, or localized violence should be mitigated (Allouche, 2011). Nevertheless, how a specific food system copes with climatic and market stress may depend on the extent to which a country is a net importer or exporter of food. Scholars have found, for example, that as food resource availability declines relative to demand, net importers of food—such as Mexico—may find themselves increasingly prone to crisis from market volatility and other shocks (Suweis et al., 2015). In Mexico, maize market integration and trade is also complicated by the fact that most maize imports are of the yellow variety. Although popular accounts of market openness suggest that U.S. imports are substituting for domestic production, yellow corn is purportedly not preferred for human consumption or for use in the tortilla industry (Appendini, 2011; Appendini, 2014). Thus, in a crisis, while yellow corn may be available in global markets, Mexico may face difficulty in sourcing white maize to meet domestic demand.

## 3. Data and Analysis

This study used disparate data sources to measure aspects of the dynamic system; these sources resolve at a variety of spatial and temporal resolutions, a fact that challenges quantitative synthesis and data integration (see table 1). The analysis thus relies on both qualitative and quantitative methods to explore the sector's dynamics. To investigate our hypotheses concerning the sensitivity of maize yields to climatic trends and to assess evidence of maize abandonment, we used production data (area planted, area harvested, volume, yield, crop failures; 1980 to 2014) from Mexico's Agriculture and Fisheries Information Service (SIAP) (Servicio de Información Agroalimentaria y Pesquera, 2016).The results are based on national-, regional-, and state-level series organized by season for rain-fed and irrigated production. The climate analysis focuses only on the spring, rain-fed yield in states of central and southern Mexico. The figures present the most recently available observations, but we also refer to results based on previously published analyses that used shorter times series that were available at when the studies were published.

To explore the sensitivity of maize yield and climatic factors, we regressed state-level detrended maize yields against agro-climatic indices and assessed model fit using out-of-sample validation. The climatic indicators are standardized anomalies derived from gridded (0.125 degree) daily precipitation and temperature data spanning 1950-2008 (available at http://clicom-mex.cicese.mx/malla). For the regression analysis, we constructed annual averages of the climate indicators at the state level from 1980 to 2008 to align with the available yield series. The variables considered in the model include maize-relevant precipitation and temperature indices (i.e., total annual precipitation, *P*; average rainy season precipitation, *W*; rainy season start date, *SRS*; share of dry days in the rainy season, *Dry*; number of hot (>30 ºC) days from June to July, *Hot*; number of cold days (<10 ºC) from June to August, *Cold*; and number of frost days (<1 ºC) from June to September, *Frost*). Each index had a grid-point-level time series of 59 values. At least one precipitation index (*P* or *W*) was always kept in the regression model, whereas other predictors were removed according to their contribution to fit. All models were fit with a 21-year sample (1980-2000), leaving 2001-2008 data for a split-sample validation test. The period of analysis was not intended to be a definitive assessment of climatic trends in maize regions, which would require a longer time series. Rather, the analysis serves as a proxy for the form of climatic stress and change that a farmer would have experienced over that period.

To evaluate the hypothesis that market integration has increased (and thus has affected the sensitivity of maize to global and sub-national market shocks and stress), we used weekly maize price data (1998-2016) from Mexico's Office of Economic Affairs via the National System for Market Information and Integration (SNIIM, or Sistema Nacional de Información e Integración de Mercados). We assessed market integration in two ways: first, by measuring the degree of covariation between Mexican and U.S. maize prices using regression, and second, by using an indicator of market thickness based on Mexican interstate trade. In the first case, we regressed the average maize price across all Mexican state markets ("national price") against the monthly lagged U.S. price (U.S. yellow #2, obtained from the U.S. Department of Agriculture Economic Research Service's Feed Grains Database, Gulf of Mexico Louisiana grain elevator) and seasonally lagged national crop loss. We conducted a similar analysis to assess differences in sub-national market integration ("thickness") using maize prices from state markets across Mexico. Fixed effects for the state, year, and a state-by-year interaction term were included as controls, and the standard errors were corrected for serial and spatial correlation by using the method described in Driscoll and Kraay (1998). The regression results are based on previously published research that used the price series from 1998-2010. In the second case, we measured the share of interstate transactions relative to all possible transactions in state Maize markets. If more maize was sold outside the state it was grown in (indicating interstate trade), market thickness increased.

To understand the dynamics of change at the level of the maize farming household, we collected household survey data (n=1,529) in three states in 2009: from the North (Sinaloa), Center (State of Mexico), and South (Chiapas) of the country. In Chiapas and the State of Mexico, Rural Development Districts (DDRs) were purposely selected on the basis of their contribution to the state's total maize production and land area in maize in 1990. Within each DDR, we used a beneficiary database for the PROCAMPO program* as a sampling frame. In Sinaloa, we used a list of registered agricultural water users in the irrigation district of Culiacán as our sampling frame, selecting four irrigation modules at random, and stratifying our sample by landholding size. In all cases, households were eligible for the survey if they had produced maize at least once in the period from 1990 to 2009, when the survey was implemented.

* A public program that provides a per-hectare subsidy to farmers planting any of nine basic staples, including maize. This program is assumed to cover the majority of maize farmers in Mexico (see Fox and Haight 2010).

Classification tree analysis (Breiman et al., 1983) was used to classify observations (households) according to reported changes in maize production (maize area change, yield change) as the outcome variables. Classification tree analysis identifies classifier variables and associated threshold values that provide the most homogenous partitioning of households with respect to the outcome variable. Homogeneity, or purity, of the subsets was measured using the Gini index. Trimming procedures recovered the rooted sub-tree with the minimum deviance or max purity among the set of all possible rooted sub-trees (Driscoll and Kraay, 1998). Standard descriptive statistical analysis of household data was also performed for cross case comparison.

## 4. Results

*4.1 What is the evidence of maize sector sensitivity to climatic and market stress?*

The accumulated vulnerability of Mexico's maize sector to both the influence of climatic stress and market liberalization could manifest as maize abandonment, as well as a reduction in maize area and yield. Such outcomes would indicate both persistent sensitivity and lack of capacity to cope and adapt in order to maintain production. Analysis of a subset of the household survey data for which there were no missing values (n= 1,459) indicated that ~11% of respondents reported abandoning maize in Sinaloa and ~ 5% in Chiapas and the State of Mexico. In Sinaloa, of the households that have maintained maize production, almost none reported decreasing maize area, and over a quarter of those sampled report increases, largely through land rentals. Approximately 31% of households in Chiapas and ~26% in the State of Mexico, however, reported reducing the area planted in maize. In Chiapas, the classification tree analysis indicated that those households that reduced maize area were more likely to be older, have land in pasture, and be from productive grain farming areas (Eakin et al., 2015). Almost all had sufficient maize area (~5 ha) not only to meet subsistence needs but also to produce a maize surplus (i.e., production >1.25 x expected consumption, based on family size and composition, (see de Janvry et al., 1995). Subsistence farming also persists in the State of Mexico with households diversifying into vegetables or alternative grains. Although farmers reported having experienced climatic stress, particularly from drought, the classification tree analysis did not associate farmers' reports of this experience with the farmers' reports of declining maize area in either Chiapas or the State of Mexico.

Data at the national, sub-national (multi-state), and state level also reflect an ambiguous picture of maize abandonment. Using the national annual agricultural survey (Servicio de Información Agroalimentaria y Pesquera, 2016) to compare 5-year averages at the beginning (1980-1984) and end (2010-2014) of the sample, we find that maize area decreased by ~ 8%. The household-level data indicate that smallholders have retreated from national markets but have not abandoned maize. Most households surveyed in Chiapas and the State of Mexico consume over half of their maize harvests domestically, even in a context of increasing income diversification and, in the State of Mexico, urbanization. Furthermore, 16% of sampled households in the State of Mexico and 50% of those in Chiapas are still participating in maize market transactions, although these transactions are largely through informal and local networks (e.g. sales to neighbors, to intermediaries, to local informal stores). Participation in such transactions occurred even in cases where the household was not producing a surplus and was also purchasing maize. In addition, 92% of households in the State of Mexico and 40% in Chiapas reported making their own tortillas from maize grain rather than commercial flour.

Interestingly, declining maize area has not resulted in a corresponding decline in production. At the national level, again relying on the national agricultural survey, maize output increased by 74%; coupled with the 8% decline in maize area, this indicates an intensification of production. Most, but not all, of the increased national production is from the irrigated sector, with output increasing over 200% but area planted increasing just 30%. A large share, ~60%, of the increased irrigated output is due to the abrupt entry of Sinaloa into commercial maize production and subsequent rapid growth. Although the rain-fed sector does not have the same dynamic growth path, output still increased by ~30% despite a 14% decline in area planted. It is clear that the rain-fed sector remains central to the Mexican maize system, constituting 57% of total output at the end of the study period.

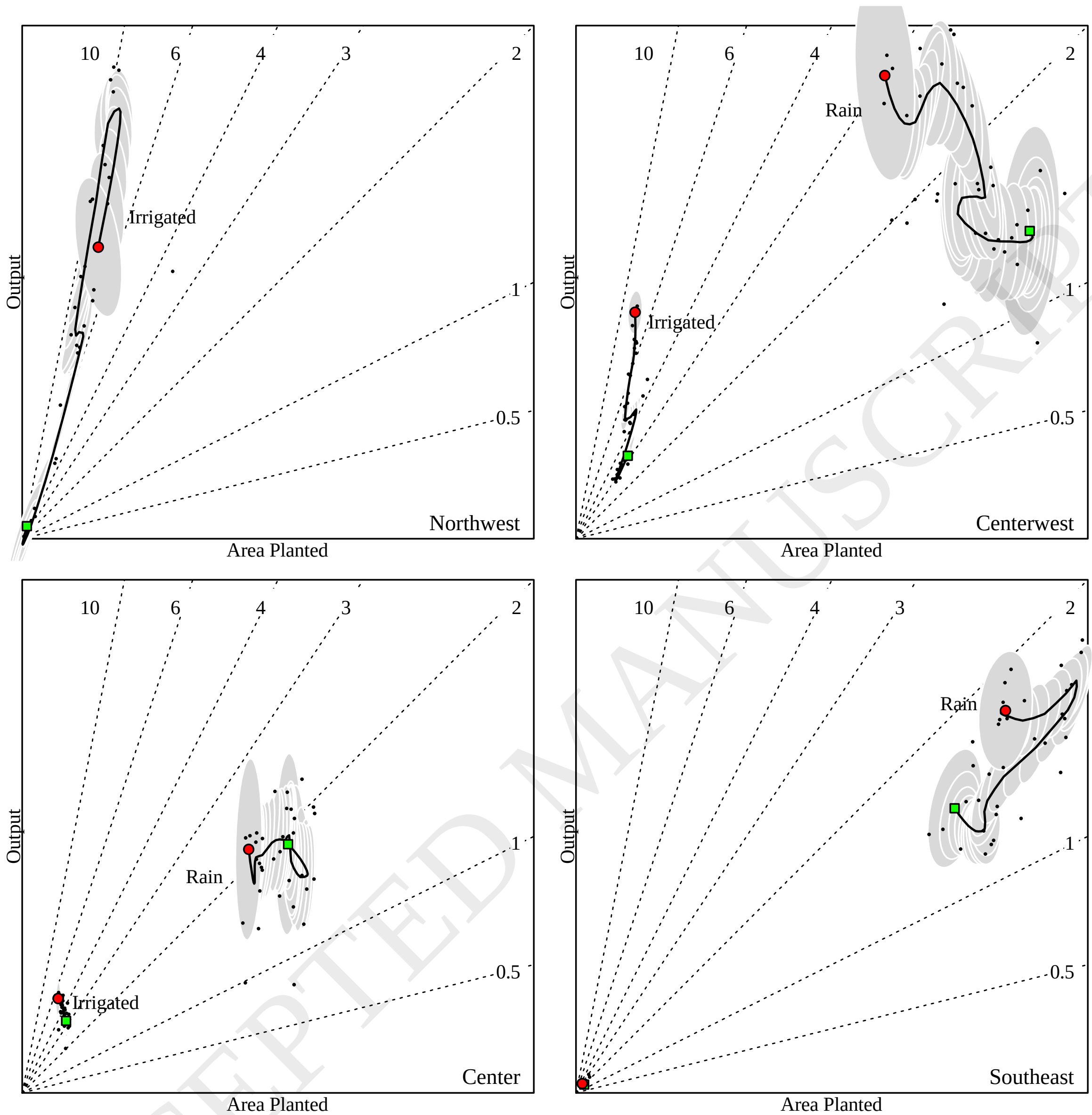


Figure 1: Evolution of production by region, 1980-2014. Each sub-national series contains 35 observations (1980-2014) for each production regime (irrigated or rain-fed) and season. Individual observations (black points) indicate the location in the space of output and area planted; rays out of the origin have equivalent yield. The green square is the mean center for 1980-84 and the red circle is the mean center for 2011-2014. Trajectories through the space defined by output and area planted are the predicted loess curves from the domains of output x year and area planted x year. Ellipses represent the uncertainty for each year based on the standard error of the loess curves.

One factor associated with national yield and production increases is the use of hybrid seeds in the Center-west and Northern irrigated states, particularly in Sinaloa (Eakin et al., 2014a). However, we found that landraces were still prevalent in the State of Mexico and Chiapas: 60% of households Chiapas and 98% in the State of Mexico report planting local landraces, compared to less than 1% in the commercially oriented irrigation districts of Sinaloa. The use of landraces is often associated with the highlands, where agro-climatic conditions are variable and often less conducive to commercial production (Perales R. et al., 2003).

In sum, we found little evidence that the maize sector has atrophied over the last several decades, irrespective of cause. While changes in maize area vary across regions, production levels have increased in all regions except the Center. This indicates intensification, likely driven by modernization in both irrigated and rain-fed sectors. Nevertheless, the household data provided no evidence of widespread maize abandonment by small- and medium-scale producers. Instead, we found that farmers in rain-fed areas reduced their maize area while persisting in subsistence maize farming in combination with other economic activities. In other words, the sensitivity of smallholders to stress in the maize sector appears to manifest in terms of retreat and diversification; such strategies are outweighed at the national level by broader trends of technological intensification, land consolidation, and new geographies of production.

*4.2 How have trends in climatic parameters affected maize yields?*

The regression of agro-climatic indices with de-trended maize yield data at the state level suggested that the predictive effect of each index varies geographically and overall tends have only a moderate effect on yield variability. The models focused only on the spring, rain-fed maize crop. The agro-climatic indices were constructed to reflect the timing of the climatic stress relative to specific phases of crop growth. The states of Guanajuato and Morelos had the best fits (adjusted $R^2$ of 0.72 and 0.57; RMSE from validation of 0.43 and 0.57, respectively), but only the total annual rainfall (P) predictor was significant with a notable effect size (1.17 and 1.61). Furthermore, the agro-climatic indices had particularly poor correlation in predicting yields in states where smallholder subsistence production is predominant, including Chiapas and the State of Mexico (adjusted $R^2$ of 0.14 and 0.30; RMSE from validation of 0.27 and 0.80, respectively), two states that were the focus of this study. The findings based on the regression analysis, however, are tentative given the relatively short time series available for analysis.

An alternative means of gauging climate impact on crops is through analyzing farmer perceptions. Most households surveyed in the State of Mexico and Chiapas reported declining maize yields (87% and 63% of households, respectively), largely attributing the decline exclusively or partially to extreme climatic events (79% and 68% of households, respectively). The classification tree analysis revealed that the households reporting yield decline in Chiapas were not only those reporting more severe and frequent extreme events but also those who tended to have a relatively higher proportion of women in the household engaged in off-farm, salaried labor. While the results are inconclusive in relation to the direction of the relationship, household economic diversification would be an expected response to declining agricultural output and extreme event impacts (Eakin, 2005). The classification tree analysis did not produce robust results for the State of Mexico, suggesting that the factors associated with yield decline among households surveyed in that state were too heterogeneous to conform to the classification tree analysis.

Despite the ambiguous results of the yield-climate analysis, the surveyed households consistently highlighted drought as the most serious threat to production, particularly in the rain-fed case studies, as signaled by 59% of farmers in Chiapas and 71% in the State of Mexico (compared to 14% of Sinaloa's irrigated producers). More respondents in Chiapas and the State of Mexico also perceived the frequency of drought to be increasing (71% and 89%, respectively) compared to Sinaloa (8%). Contrasting sharply with the State of Mexico and Chiapas, Sinaloan respondents uniformly reported yield increases, which they attributed to improved seeds and technology. Irrigation and the use of commercial technologies likely had a significant effect on the perception of risk by Sinaloa's farmers (Rodriguez et al., 2017).

*4.3 How has the maize sector been affected by market integration?*

Contrary to the popular narrative on NAFTA and maize in Mexico, the regression results indicate that the thickness of both national and sub-national markets increased long before the market was fully liberalized under NAFTA and that the markets have been integrated for some time. We measured thickness, an indicator of market integration, by the responsiveness of domestic market prices to the U.S. price: as markets become more integrated (thick), we would expect to observe greater price co-variation. Over the period for which we have data, 1998-2010, we found that the extent of co-movement varied but remained significant throughout (see also Davenport et al., 2016). Similarly, in our analysis of sub-national wholesale markets, we found that Mexican maize prices were already responsive to U.S. prices in 1998, roughly ten years before the official removal of all tariffs on maize trade between the U.S. and Mexico.[¶]

[¶] While tariffs were not officially removed until 2008, maize trade was in fact tariff free following the signing of NAFTA. Although the Mexican government was allowed to apply import tariffs for import volumes above an established threshold, it did not do so in the 1990s, often citing drought and production shortfalls.

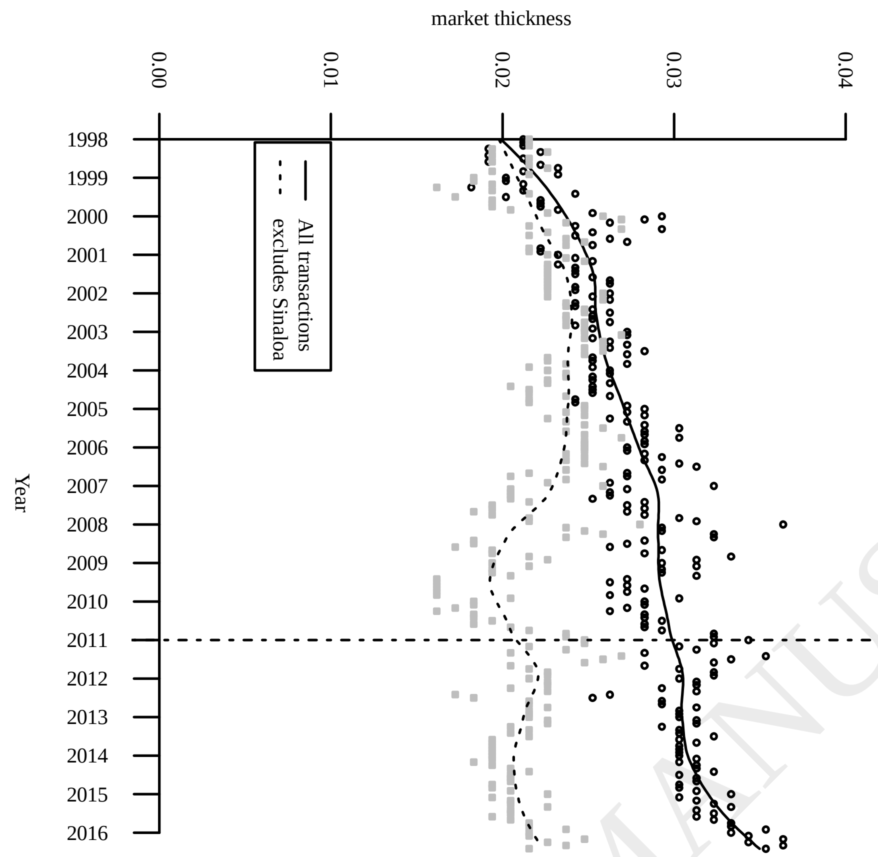


Figure 2: National trend in market thickness (1998-2016). The market thickness measure is based on transaction matrices that indicate for each year and month whether maize grown in a particular state was sold in any of the 30 state wholesale markets. The time series is from January 1998 to June 2016, so there are 205,200 potential transactions (228 x 30 x 30). Only 6,132 transactions are recorded. The figure displays market thickness measures including and excluding Sinaloa for each of the 228 periods. The smooth lines are loess curves.

The analysis of market thickness in Mexico, based on computing the number of active sub-national trade linkages in each period relative to all possible linkages, also demonstrates increased domestic connectivity over time (Fig. 2). These findings could signal that the Mexican maize market is now more sensitive to international market shocks and potentially less sensitive to domestic crop losses. For example, for the period 1998-2000, a one standard deviation change in crop loss is associated with a 0.16

standard deviation change in the Mexican price. By the end of the sample, 2009-2010, the same change in crop loss corresponds to only a 0.04 standard deviation change in the Mexican price.

Nevertheless, sensitivity to both internal and external shocks also depends on the nature of market integration and the structure of the market (Suweis et al., 2015). In the case of Mexico, the observed increase in domestic market thickness, which could indicate less sensitivity to international shocks, is largely driven by an increase in exports of maize from Sinaloa to other sub-national wholesale markets (Fig. 2). Because maize production in Sinaloa is almost entirely irrigated, the thickness resulting from increased trade with Sinaloa may lead to *less* sensitivity to local climate shocks in rain-fed areas. Sub-national markets can also become *more* sensitive to extreme events affecting Sinaloa's production. One such extreme event occurred in early 2011, when 85% of Sinaloa's maize area was affected by frost, amounting to immediate losses of 5.3 million tons and over $12 billion pesos. Much of the area was subsequently replanted (Government of Sinaloa, 2012). As evident in Fig. 3, the losses translated into a significant price shock in Sinaloa and other state maize markets.

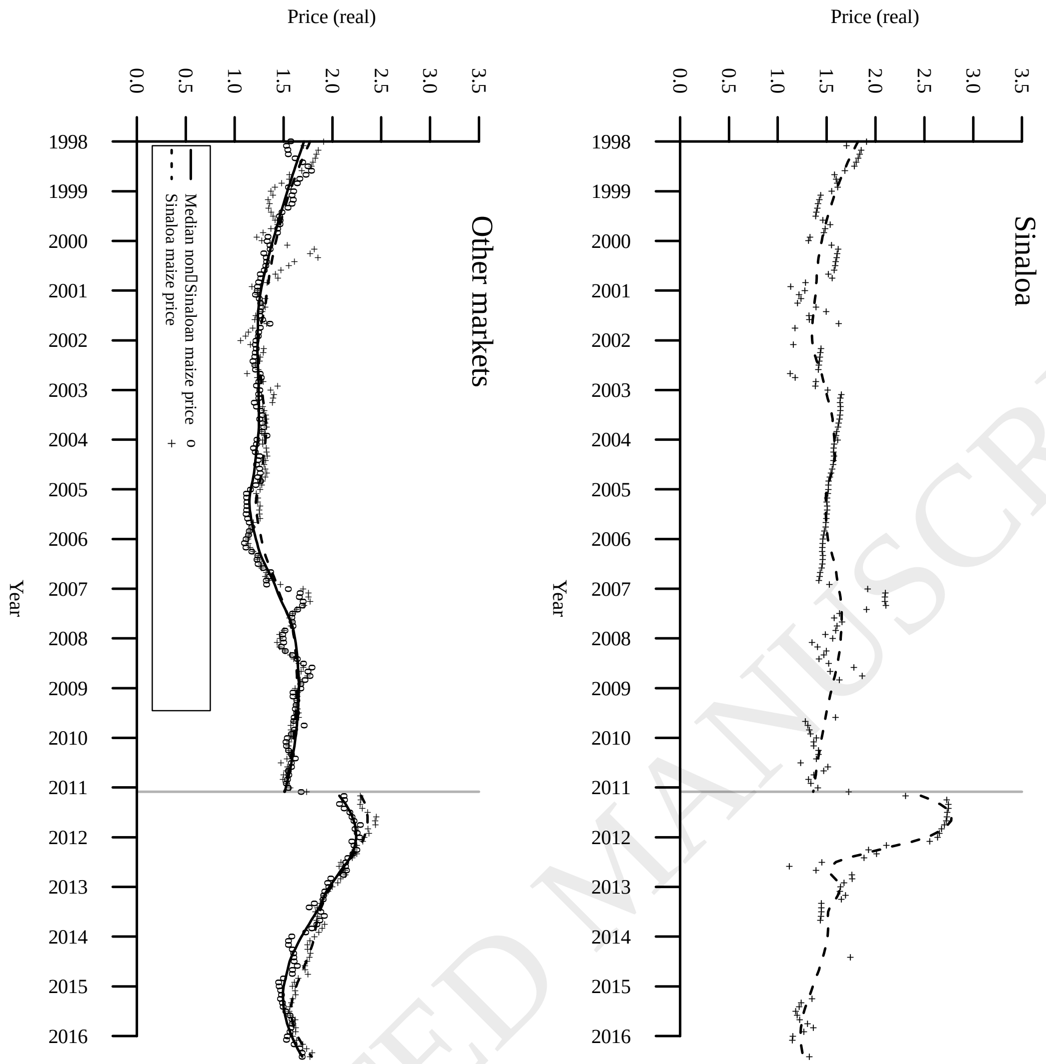


Figure 3: Sub-national market sensitivity to the Sinaloa frost of 2011. The price series is from January 1998 to June 2016 (228 observations). The upper plot displays the price of maize grown and sold in Sinaloa. The lower plot displays two series: the average price of maize grown in Sinaloa and sold outside of Sinaloa and the average price of maize grown and sold outside of Sinaloa. Smooth lines are loess curves with a break at February 2011.

*4.4 What has been the role of domestic policy in the maize system's evolving vulnerability?*

Contrary to much of the discourse on neoliberalism and Mexico's maize sector, we found that the public sector has continued to play a strong role over the period of agriculture market liberalization, particularly in relation to enhancing resource access and investment in large-scale commercial production in Mexico's Northwest (Appendini, 2014). The state of Sinaloa, traditionally known for irrigated vegetable production, emerged as a primary beneficiary of the new support programs for maize in the 1990s. Farmers in Sinaloa particularly benefited from two programs under the umbrella program Agencia de Servicios a la Comercialización y Desarrollo de Mercados Agropecuarios (ASERCA), a program designed to support farmers' participation in commercial markets: Procampo, or *Programa de Apoyos Directos al Campo*, an income subsidy offered to all farmers of basic staples, and *Apoyos a la Comercialización*, a program for incentivizing commercialization in formal markets. Although Sinaloa has only 0.6% of the maize sector's farm population, the state has typically received the lion's share of ASERCA's resources, for example, 68% of the funds from ASERCA's income support program and 80% of the funds from the Advanced Purchase Program in 2007-2008. Of the households surveyed in Sinaloa, 89% reported receiving Procampo funds, two-thirds participated in other ASERCA programs, and over three-quarters reported receiving insurance and extension services. Procampo was designed to support the transition of small-scale farmers from basic grains to higher-value crops. Nevertheless, a disproportionate share of Procampo funds go to larger-scale producers (Fox and Haight, 2010). *Apoyos a la Comercialización* also has subsidized market transactions among larger-scale irrigated commodity producers and the agri-food industry to diminish market risk. Over the period of analysis, the maize-tortilla commodity chain became increasingly concentrated, such that a relatively small number of entrepreneurial farmers (largely from Sinaloa), corporate traders (Cargill and others), and the maize flour industry (Grupo Gruma/Maseca) now dominate formal maize market transactions.

In contrast to Sinaloa, producers surveyed in the State of Mexico and Chiapas reported little involvement in public support programs, and negligible (<5%) access to formal agricultural services such as insurance and extension. Just under two-thirds reported receiving Procampo funds (61% and 65%, respectively), despite the fact that the households were listed on the beneficiary list. No households participated in the commercialization support programs of ASERCA. Furthermore, none of the respondents reported participating in PROMAF (*Proyecto Estratégico de Apoyo a la Cadena Productiva de los Productores de Maíz y Frijol*), the government's program designed to support productivity improvements and climate resilience for smallholder maize farmers.

## 5. Implications for Maize System Change and Vulnerability

Rather than a uniform trend towards the obsolescence of the smallholder sector as a result of climate stress and market integration, we found a complex and geographically heterogeneous pattern of maize persistence, market retreat, land consolidation, and even maize area growth in response to a highly varied social, political, ecological, and economic landscape. While demographic and climatic stress may alter maize productivity and land use in the near future (Ureta et al., 2012), our analysis suggests that over the last three decades, climatic stress has not been a major driver of national-level change. Rather, shifts in domestic policy priorities and programs have been particularly influential on the sector's evolution and on farm-level production strategies, altering the landscapes and livelihoods in which future climate trends and impacts will occur. The analysis does not indicate widespread maize abandonment over the study period. In fact, maize production increased nationally over the period of liberalization and climatic variability, and maize land area decreased less than might be expected. These results indicate that nationally, the sector was less sensitive to global change than has often been described and that technological investments and domestic policy have perhaps offset local and sub-national sector losses. Nevertheless, such findings are not indicative of the sector's future vulnerability. As the maize system has evolved, indications have emerged that its exposure, sensitivity and capacities are also changing, advising against complacency.

Changes in the structure and geography of maize in Mexico—namely, the government's focus on incentivizing maize expansion in Sinaloa, contributing to maize stagnation in the Center and South—complicate understanding of the effects of both climatic stress and market liberalization. In Mexico, the liberalization process, which is popularly associated with the implementation of NAFTA, exerted influence largely through domestic policy change, particularly in terms of subsidy programs such as ASERCA. The impact of this policy shift is particularly prominent in Sinaloa, which now receives significantly more public investment for maize production than it did at the beginning of the study period and in comparison to other states (Fox and Haight, 2010), resulting in a “boom” in maize production that was unprecedented in Mexican history (Eakin et al., 2014a). In essence, this investment created a differentiated landscape of adaptive capacity and, in turn, a new context of vulnerability. The penetration of Sinaloan white maize into national markets is in large part responsible for the increased thickness in state wholesale markets. This change in the structure of the maize market now has implications for the sector’s sensitivity to price shocks. The dissemination of Sinaloa’s maize likely decreases the sensitivity of the national market to U.S. price shocks; however,, the country may now be far more sensitive to idiosyncratic shocks that affect Sinaloa’s production capacity.

Results from this study show that in the context of these policy changes, small-scale, rain-fed producers are not leaving their maize provisioning to the vagaries of the market.  Smaller-scale production continues to persist for household consumption, and maize produced by smallholders is circulating in local, informal markets. While difficult to precisely calculate, the persistence of smallholder production may be contributing to regional food security and could represent an adaptive resource at the national scale for the near future. From National Agricultural Census data, we estimate that the farm units of less than 5 ha produced 37% of the total national production volume in 2007. Estimating consumption conservatively at 250kg/cap/day, this volume would exceed the human subsistence needs of Mexico’s most rural population (i.e., the estimated 25 million living in villages with populations < 2,500). Smallholder maize farming is thus likely continuing to provide food security for producing households, as well as meeting community maize needs through local markets. The continued salience of maize farming likely reflects the lack of alternative livelihood opportunities in agricultural and non-farm labor markets, as well as a cultural preference for home-grown maize and homemade tortillas, in spite of the increasingly urban and globalized context of production (Appendini et al., 2008; Lerner et al., 2014). Economic conditions and cultural preferences, have been shown to be particularly salient in maize farmers' maintenance of local landrace cultivation in Chiapas (Bellon and Hellin, 2011; Brush and Perales, 2007) and the persistence of maize cultivation in and around the metropolitan region of Toluca, where the *campesino* identity is culturally significant (Lerner et al., 2014).

Based on this analysis, Mexico's smallholder maize sector is surprisingly resilient: the sector has weathered significant disturbance and change while remaining important in livelihoods and landscapes. Underlying the disparate case study evidence of maize abandonment (Klooster, 2003), crop diversification (Barkin, 2006), niche maize market exploration (Keleman and Hellin, 2009), and diversification into non-farm economic activities (Lerner and Appendini, 2011) is a story of smallholder retreat from formal commercial markets and persistence in subsistence activities. In other words, smallholders have adapted their livelihoods to new circumstances, although with little external support, while maintaining a cultural and environmental commitment to maize.

Smallholders have always pursued strategies that enable them flexibility in the face of both environmental and political-economic change, and maize has played a central role in such strategies. Smallholders plant seed varieties well-suited to the agro-ecological conditions of their parcels (Perales R. et al., 2003) and rely on non-farm income sources that buffer their maize production in times of volatility (see also Eakin, 2005). Indeed, the relatively weak signal between climate and yield in the rain-fed regions is perhaps indicative of farmers' historic adaptation of seed varieties and farming techniques to local agro-climatic conditions (Mercer et al., 2012). At the national scale, as smallholders have retreated from commercial markets, Sinaloa's irrigated winter maize production has helped mediate variability in domestic supplies from localized, idiosyncratic shocks. With the growth of Sinaloan production, Mexico—in most years—produces enough white maize for domestic consumption, while continuing to import yellow maize for livestock feed and industrial use.

Nevertheless, while the emergence of Sinaloa as a major supplier of maize for national consumption is a modernization success story, the impact of the 2011 frost in Sinaloa illustrates that a geographic concentration of production potentially exacerbates vulnerability at the national scale. It is evident that Sinaloan harvests are not invulnerable to shocks, despite the availability of irrigation. The Sinaloan farmers sampled by the 2009 survey expressed relatively little concern with climate impacts, yet two years later they faced almost a complete loss of their harvest due to frost. The following year, drought and limited water availability in reservoirs —partly as a result of an aggressive replanting effort immediately following the frost—translated into a 40% reduction in planted area from 2011(Government of Sinaloa, 2012), as can be seen in Fig. 1 (NW Region). Climate change scenarios anticipate significant drying and warming trends on the Pacific Coast (Prieto-González et al., 2011; Seager and Vecchi, 2010) that are likely to affect the longer-term viability of the surface water irrigation on which the sector depends.

The dramatic increase in production in Sinaloa required a significant financial investment for both production and movement of grain. The federal government underwrote much of this investment, potentially at the expense of investment in market infrastructure in other regions (Appendini, 2014; Eakin et al., 2014a). The benefit of this public investment is thus concentrated among a relatively small group of farmers and corporate agents in the maize supply chain; opportunities for wider participation in formal markets and associated capacity building are limited in other regions. The significant mobilization of public resources following the frost of 2011 illustrates the financial implications of a national agricultural strategy in which "too big to fail" conditions have been created through market concentration (Eakin et al., 2014a).

## 6. Conclusion

As climate variability increases and agricultural producers are more connected to global marketplaces and price volatility, the sensitivity of food systems to both exogenous and endogenous change is of upmost importance (Suweis et al., 2015). While the threats of climate change and globalization are often presented as uncontrollable forces on farmers' existence, public policy, politics, culture, and preferences motivate and mediate livelihood and landscape outcomes. In Mexico's maize system, coping with such change depends on diversifying sources of white maize imports, maintaining an aggregate national productivity to meet increasing demand, and maintaining the geographic and production-system diversity that enhances flexibility in responding to increasing environmental and economic uncertainty in global and domestic maize markets. Mexico currently encompasses a great diversity of maize producers in terms of scale, production methods, and agro-climatic zones. This analysis of just three states examined farms of less than 2 ha to over 50 ha, including farms using irrigation and mechanization on the coastal plains of Sinaloa and farms cultivating by hand-held hoe and stick in the rough terrain of Chiapas' highlands. Focusing on one region through policy support creates conditions conducive to greater production efficiency and can be instrumental in generating higher yields, potentially at the cost of introducing new vulnerabilities into food system dynamics. As has been documented in other parts of the world, rural development is complex, and decisions by actors at all levels of the food system are continually shaping its evolution (Hazell et al., 2010, Rigg et al., 2016). The geographic and social heterogeneity in the Mexican maize production system could be considered a strategic asset in enhancing resilience to external and internal shocks. Nevertheless, the benefits that this heterogeneity brings to the maize system are currently not supported in domestic policy.

Mexico's situation has more broad lessons. In the U.S., for example, widespread and severe drought conditions have led to impacts on the primary region of horticultural crop production with implications for national food system vulnerability (Hodbod and Eakin, 2015). Globally, there is increasing concern over the ability to produce enough food for a growing population, and smallholders must play a role in any response to this challenge (Foley et al., 2011; Godfray et al., 2010). While smallholders across the world are often considered particularly vulnerable to climatic shocks and market globalization (Ribot et al., 1996; Morton, 2007; Christoplos, 2010) there is also an increasing acknowledgement of the critical role these producers play in regional food security, economic vitality, and political stability (World Bank, 2007; Vermeulen et al., 2012; Birner and Resnick, 2010).

Governments and international agencies are providing new attention to small-scale production in sub-Saharan Africa, for example, in an effort to accelerate progress towards the Sustainable Development Goals (Pingali, 2012). Additionally, "climate smart agriculture"—a suite of technologies and approaches tailored to the agro-ecological conditions and climatic risks of smallholder farms—is increasingly being adopted by public agricultural research institutions in many developing regions (Lipper et al., 2014).

Case study research is essential to document the processes and interactions that are often invisible at more aggregate levels of analysis and can be an essential source of novel hypotheses and insights into social-ecological processes. Focusing on case studies alone, however, can lead to a distorted perspective on broader-scale contemporary trends and patterns. The highly interconnected, multi-scalar and multi-stressor nature of food system change demands an approach that explicitly addresses this complexity. This lesson is not just applicable in the developing world but in all regions with agricultural potential. Disparities in data quality and availability across spatial and temporal scales can be perceived as barriers, particularly if the aim is a to create a fully integrated, system dynamic model of agricultural change. Nevertheless, the use of existing secondary data, complemented by additional insights from carefully selected sites of primary data collection, can create a more complete assessment. Multi-scalar analyses such as this can bring needed attention to the function of geographic heterogeneity, diversity in modes of production, and the viability of multiple pathways to market participation in achieving food policy goals.

**Acknowledgements**
Funding for this research was provided by the National Science Foundation, Grant 0826871. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. We greatly appreciate the assistance of Ma.G. Quijada and J. L. Armenta in the data collection process, and the generosity of the public officials, regional experts and farmers in Chiapas, Mexico and Sinaloa who gave their time to the research team.

**References**

Akram-Lodi, A.H., Kay, C., 2010. Surveying the agrarian question (part 1): unearthing foundations, exploring diversity. J. Peasant Stud. 37, 177–202.

Allouche, J., 2011. The sustainability and resilience of global water and food systems: Political analysis of the interplay between security, resource scarcity, political systems and global trade. Food Policy 36, Supplement 1, S3–S8. https://doi.org/http://dx.doi.org/10.1016/j.foodpol.2010.11.013

Appendini, K., 2014. Reconstructing the maize market in rural Mexico. J. Agrar. Chang. 14, 1–25.

Appendini, K., 2011. La integración regional del sistema maíz-tortilla, in: Appendini, K., Gómez, G.R. (Eds.), La Paradoja de La Calidad: Los Alimentos Mexicanos En La Región de América Del Norte. El Colegio de México, México, Districto Federal .

Appendini, K., 2001. De la milpa a los tortibonos : la restructuracion de la politica alimentaria en Mexico, 2a ed. El Colegio de Mexico Centro de Estudios Economicos : Instituto de Investigaciones de las Naciones Unidas para el Desarrollo Social, Mexico.

Appendini, K., Cortes, L., Díaz, V., 2008. Estrategias de seguridad alimentaria en ls hogares campesinos: la importancia de la calidad del maíz y la tortilla, in: Appendini, K., Torres-Mazuera, G. (Eds.), ¿Ruralidad Sin Agricultura? Perspectivas Multidisciplinarias de Una Realidad Fragmentada. El Colegio de México, Mexico, D.F., pp. 103–127.

Barkin, D., 2006. Building a future for rural Mexico. Lat. Am. Perspect. 33, 132–140.

Bellon, M., Hellin, J., 2011. Planting hybrids, keeping landraces: Agricultural modernization and tradition among small-scale maize farmers in Chiapas, Mexico. World Dev. 39, 1434–1443.

Birner, R., Resnick, D., 2010. The political economy of policies for smallholder agriculture. World Dev. 38, 1442–1452.

Breiman, T., Friedman, J.H., Olshen, R.A., Stone, C.J., 1983. Classification and Regression Trees. Wadsworth, Belmont, CA.

Brush, S.B., Perales, H.R., 2007. A maize landscape: Ethnicity and agro-biodiversity in Chiapas, Mexico.

Agric. Ecosyst. Environ. 121, 211–221.

Carlsen, L., 2013. Under Nafta, Mexico suffered, and the United States felt its pain. New York Times.

Carton de Grammont, H., 2009. La desagrarización del campo mexicano. UAEMex 50, 13–55.

Christoplos, I., 2010. The Multiplicity of Climate and Rural Risk, DIIS Working Paper 2010:08. Danish Institute for International Studies, Copenhagen, Demark.

Dasgupta, P., Morton, J.F., Dodman, D., Karapınar, B., Meza, F., Rivera-Ferre, M.G., Sarr, A.T., Vincent, K.E., 2014. Rural areas, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (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 of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 613–657.

De Janvry, A., Sadoulet, E., 2001. Income strategies among rural households in Mexico: The role of off-farm activities. World Dev. 29, 467–480.

de Janvry, A., Sadoulet, E., Deanda, G., 1995. NAFTA and Mexico's maize producers. World Dev. 23, 1349–1362.

Driscoll, J.C., Kraay, A.C., 1998. Consistent Covariance Matrix Estimation with Spatially Dependent Panel Data. Rev. Econ. Stat. 80, 549–560.

Dube, O., Garcia Ponce, O., Thom, K., 2014. From maize to haze: Agricultural shocks and the growth of the Mexican drug sector. Cent. Glob. Dev. Work. Pap.

Eakin, H., 2005. Institutional change, climate risk, and rural vulnerability: Cases from central Mexico. World Dev. 33, 1923–1938.

Eakin, H., Appendini, K., 2008. Livelihood change, farming, and managing flood risk in the Lerma Valley, Mexico. Agric. Human Values 25, 555–566.

Eakin, H., Appendini, K., Perales, H., Sweeney, S., 2015. Correlates of Maize Land and Livelihood Change Among Maize Farming Households in Mexico. World Dev. 70, 78–91.

Eakin, H., Bausch, J.C., Sweeney, S., 2014a. Agrarian Winners of Neoliberal Reform: The "maize boom" of Sinaloa, Mexico. J. Agrar. Chang. 14, 26–51.

Eakin, H., Lemos, M.C., Nelson, D.R., 2014b. Differentiating capacities as a means to sustainable climate change adaptation. Glob. Environ. Chang. 27, 1–8. https://doi.org/10.1016/j.gloenvcha.2014.04.013

Eakin, H., Perales R., H., Appendini, K., Sweeney, S., 2014c. Selling maize in Mexico: The persistence of peasant farming in an era of global markets. Dev. Change 40, 133–155.

Ericksen, P., 2008. Conceptualizing food systems for global environmental change research. Glob. Environ. Chang. 18.

Feng, S., Krueger, A.B., Oppenheimer, M., 2010. Linkages among climate change, crop yields and Mexico–US cross-border migration. Proc. Natl. Acad. Sci. U. S. A. DOI: 10.10. https://doi.org/10.1073/pnas.1002632107

Fitting, E., 2006. Importing Corn, Exporting Labor: The neoliberal corn regime, GMOs, and the erosion of Mexican biodiversity. Agric. Human Values 23, 15–26.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., O'Connell, C., 2011. Solutions for a cultivated planet. Nature 478, 337–42. https://doi.org/10.1038/nature10452

Fox, J., Haight, L., 2010. Subsidios para la desigualdad: las políticas públicas del maíz en México a partir del libre comercio.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–8. https://doi.org/10.1126/science.1185383

González Alvarado, R., 2012. Maize and Indigenous Communities of Oaxaca: Two Victims of Neoliberalism, in: Weaver, T., Greenberg, J., Alexander, W.L. (Eds.), Neoliberalism and Commodity Production in Mexico . University Press of Colorado, pp. 99–114.

Gourdji, S.M., Sibley, A.M., Lobell, D.B., 2013. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. Environ. Res. Lett. 024041, (10pp).

Government of Sinaloa, 2012. Segundo Informe de Gobierno. Gobierno del Estado de Sinaloa, Culiacán, Sinaloa.

Hazell, P., Poulton, C., Wiggins, S., Dorward, A., 2010. The Future of Small Farms: Trajectories and Policy Priorities. World Dev. 38, 1349–1361. https://doi.org/http://dx.doi.org/10.1016/j.worlddev.2009.06.012

Hodbod, J., Eakin, H., 2015. Adapting a social-ecological resilience framework for food systems. J. Environ. Stud. Sci. 5, 474–484.

Instituto Nacional de Estadística y Geografía (INEGI), 2007. Censo Agrícola, Ganadero y Forestal 2007.

Keleman, A., Hellin, J., 2009. Specialty maize varieties in Mexico: A case study in market-driven agro-biodiversity conservation. J. Lat. Am. Geogr. 8, 147–174.

Klooster, D., 2003. Forest transitions in Mexico: Institutions and forests in a globalized countryside 55, 227–237.

Lerner, A.M., Appendini, K., 2011. Dimensions of peri-urban maize production in the Toluca-Atlacomulco valley, Mexico. J. Lat. Am. Geogr. 10, 87–106.

Lerner, A.M., Eakin, H., Sweeney, S., 2013. Understanding peri-urban livelihoods through an examination of maize production in the Toluca Metropolitan Area, Mexico. J. Rural Stud. 30, 52–63.

Lerner, A.M., Sweeney, S., Eakin, H., 2014. Growing buildings in corn fields: Urban expansion and the persistence of maize in the Toluca Metropolitan Area, Mexico. Urban Stud. 51, 2185–2201.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Sen, P.T., Sessa, R., Shula, R., Tibu, A., Torquebiau, E.F., 2014. Climate-smart agriculture for food security. Nat. Clim. Chang. 4, 1068. https://doi.org/10.1038/nclimate2437

Lobell, D., Ortiz-Monasterio, J.I., Asner, G.P., Matson, P.A., Naylor, R., Falcon, W.P., 2005. Analysis of wheat yield and climatic trends in Mexico. F. Crop. Res. 94, 250–256.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate Trends and Global Crop Production Since 1980. Science (80-. ). 333, 616–620. https://doi.org/10.1126/science.1204531

Manuel-Navarrete, D., Pelling, M., Redclift, M., 2011. Critical adaptation to hurricanes in the Mexican Caribbean: Development visions, governance structures, and coping strategies. Glob. Environ. Chang. 21, 249–258.

Mercer, K., Perales R., H., Wainwright, J.D., 2012. Climate change and the transgenic adaptation strategy: Smallholder livelihoods, climate justice and maize landraces in Mexico. Glob. Environ. Chang. 22, 495–504.

Monterroso Rivas, A.I., Conde Álvarez, C., Rosales Dorantes, G., Gómez Díaz, J.D., Gay García, C., 2010. Assessing current and potential rainfed maize suitability under climate change scenarios in México. Atmósfera 24, 53–67.

Morton, J., 2007. The impact of climate change on smallholder and subsistence agriculture. PNAS 104, 19680–19685.

O’Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L., West, J., 2004a. Mapping vulnerability to multiple stressors: climate change and globalization in India. Glob. Environ. Chang. 14, 303–313.

O’Brien, K., Sygna, L., Haugen, J.E., 2004b. Vulnerable or resilient? A multi-scale assessment of climate impacts and vulnerability in Norway. Clim. Change 64, 193–225.

O’Brien, K.L., Leichenko, R.M., 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. Glob. Environ. Chang. Policy Dimens. 10, 221–232.

Perales R., H., Brush, S.B., Qualset, C.O., 2003. Landraces of maize in central Mexico: An altitudinal transect. Econ. Bot. 57, 7–20.

Pingali, P.L., 2012. Green Revolution: Impacts, limits, and the path ahead. PNAS 109, 12302–12308.

Prieto-González, R., Cortés-Hernández, V.E., Montero-Martínez, M.J., 2011. Variability of the standardized precipitation index over México under the A2 climate change scenario. Atmósfera 24, 243–249.

Ranum, P., Peña-Rosas, J.P., Garcia-Casal, M.N., 2014. Global maize production, utilization, and consumption. Ann. N. Y. Acad. Sci. 1312, 105–112.

Ribot, J.C., Magalhaes, A.R., Panagides, S.S., 1996. Climate Variability, Climate Change and Social Vulnerability in the Semi-arid Tropics.

Rigg, J., Salamanca, A., Thompson, E.C., 2016. The puzzle of East and Southeast Asia's persistent smallholder. J. Rural Stud. 43, 118–133. https://doi.org/http://dx.doi.org/10.1016/j.jrurstud.2015.11.003

Rodriguez, N., Eakin, H., De Frietas Dewes, C.F., 2017. Perceptions of climate trends among Mexican maize farmers. Clim. Res. 72, 183–195.

Seager, R., Vecchi, G.A., 2010. Greenhouse warming and the 21st century hydroclimate of southwestern North America. Proc. Natl. Acad. Sci. U. S. A. 107, 21277–21282. https://doi.org/10.1073/pnas.0910856107

Semple, K., 2017. Mexico ready to play the corn card in trade talks. New York Times.

Servicio de Información Agroalimentaria y Pesquera, 2016. Anuario Estadístico de la Producción Agrícola (Maíz grano, Zea Mays).

Silva, J.A., Eriksen, S., Ombe, Z.A., 2010. Double exposure in Mozambique's Limpopo River Basin. Geogr. J. 176, 6–24. https://doi.org/10.1111/j.1475-4959.2009.00343.x

Suweis, S., Carr, J.A., Maritan, A., Rinaldo, A., D'Odorico, P., 2015. Resilience and reactivity of global food security. Proc. Natl. Acad. Sci. - PNAS 112, 6902–6907. https://doi.org/10.1073/pnas.1507366112

Ureta, C., Martinez-Meyer, E., Perales, H.R., Alvarez-Buylla, E.R., 2012. Projecting the effects of climate change on the distribution of maize races and their wild relatives in Mexico. Glob. Chang. Biol. 18, 1073–1082. https://doi.org/10.1111/j.1365-2486.2011.02607.x

Vermeulen, S.J., Aggarwal, P.K., Ainslie, A., Angelone, C., Campbell, B.M., Challinor, A.J., Hansen, J.W., Ingram, J.S.I., Jarvis, A., Kristjanson, P., Lau, C., Nelson, G.C., Thornton, P.K., Wollenberg, E., 2012. Options for support to agriculture and food security under climate change. Environ. Sci. Policy 15, 136–144. https://doi.org/10.1016/j.envsci.2011.09.003

Wise, T.A., 2009. Agricultural dumping under NAFTA: Estimating the costs of US agricultural policies to Mexican producers. Tufts University.

World Bank, 2007. World Development Report 2008 : Agriculture for Development. The World Bank, Washington, D.C.