The Farm Size - Productivity Relationship in the Wake of Market Reform: An Analysis of Mexican Family Farms

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I. Introduction

Beginning with the seminal work of Sen (1962), economists have documented an inverse relationship between farm size and land productivity throughout much of the developing world (Bardhan, 1973; Berry and Cline, 1979; and Barrett et al., 2010, among others). This inverse relationship has been found in a broad range of geographies, time periods, and crop mixes, and has been featured in discussions of development policy, including land reform (Lipton, 2009) and the future of small farms (Wiggins et al., 2010).

The regularity with which an inverse relationship between farm size and land productivity is observed led to many theoretical explanations for the phenomenon. Early explanations centered around multiple market failures (Sen, 1966; Eswaran and Kotwal, 1986), asymmetric information (Feder, 1985), and risk aversion among farmers (Barrett, 1996). A second set of explanations emphasize empirical issues such as omitted variables, with an emphasis on soil quality (Bhalla and Roy, 1988; Benjamin, 1995; Assunção and Braido, 2007), and systematic measurement error in farm size and/or output (Lamb, 2003; Carletto et al., 2013; Gourlay et al., 2019; Desiere and Jolliffe, 2018; Abay et al., 2019). Empirical studies have typically found that existing theory fails to fully explain the observed inverse relationship, generating a body of mixed and at times contradictory evidence.

Helfand and Taylor (2021) illustrate how the choice of productivity measure can alter the relationship observed and how it can obscure a changing relationship between farm size and total factor productivity, the more relevant productivity measure. They find a dynamic relationship between farm size and total factor productivity in the rapidly modernizing agricultural regions of Brazil, contributing to an emerging literature that documents changing farm size – productivity relationships as agricultural sectors modernize and develop (Foster and Rosenzweig, 2017; Deininger et al., 2018; Rada and Fuglie, 2019). In this paper the hypothesis of a dynamic farm size – productivity relationship is extended to the context of Mexico, identifying the relationship in a panel of family farms from the Mexican Family Life Survey (MxFLS) and testing for changes over the sample period of 2002-2009.

Mexico is an interesting case for assessing changes in the farm size – productivity relationship because of its long history of land reform and the recent agricultural policy reforms that began in the 1990s as the North American Free Trade Agreement (NAFTA) took effect. These policies are a prime example of the Washington Consensus, liberalizing markets for land, agricultural inputs, and agricultural output in Mexico with the objective of accelerating the modernization, competitiveness, and productivity of the agricultural sector and the broader economy. Agricultural policy reform during this period included a phasing out of agricultural tariffs, the strengthening of property rights and reform of the *ejido* system of land tenure (Procede), and the withdrawal of government price supports in agricultural input and output markets, replaced with a system of direct payments to impacted farmers (Procampo).

An environment with such market reforms, if successful, is expected to diminish the multiple market failure explanation of the inverse relationship between farm size and productivity, and any observed inverse relationship might weaken accordingly. Berry and Cline (1979) found evidence of a weakening inverse relationship between farm size and productivity between 1940 and 1960 in Mexico. In one study estimating the contemporary farm size – productivity relationship in Mexico, Kagin et al. (2016) document an inverse relationship between farm size and total factor productivity in the early 21st century, driven in part by an inverse relationship between farm size and efficiency.

We test for changes in the farm size – productivity relationship in the first decade of the 21st century and, contrary to expectations, find that an inverse relationship exists and has remained strong in the wake of Mexico's market reforms. We explore the relationship further by estimating a stochastic production frontier. While frontier productivity growth has increased rapidly for larger farms, reducing the inverse relationship at the frontier, the average relationship has remained unchanged due to more rapidly increasing technical inefficiency among the larger farms in the sample. This finding highlights the need for policies that support family farms' transitions towards modern agriculture and adaptation to market liberalization in Mexico.

The paper is organized in sections that introduce the empirical methodology (II), describe the data (III), and present the empirical results (IV). Section V concludes with policy recommendations for Mexican agriculture and research implications.

II. Empirical Methodology

As discussed in Helfand and Taylor (2021), land productivity is a partial measure of productivity and does not account for the use of inputs other than land. Where other inputs are used in production, failing to account for the use of those resources potentially introduces bias into estimates of the relationship between farm size and productivity if the intensity of input use (inputs per hectare) varies with farm size. Controlling for all inputs in agricultural production can be accomplished with estimation of a production function, uncovering TFP, a comprehensive and preferable measure of productivity.

We use two complementary approaches to explore the relationship between farm size and TFP with a panel of Mexican family farms. First, we use an average production function to estimate average TFP and its relationship with farm size. Second, we use a stochastic production frontier to estimate the relationship between both TFP along the technological frontier and technical inefficiency, identified as deviations from the frontier. TFP change over time can be decomposed into changes in the technological frontier and changes in deviations from the frontier (Coelli et al., 2005 and Kumbhakar et al., 2015).

As is standard in the literature, we identify TFP by estimating a Cobb-Douglas production function with inputs measured per hectare, implicitly imposing constant returns to scale on the production technology. In such a setting, the inclusion of a measure of farm size as an explanatory variable identifies any relationship between farm size and TFP (Helfand and Taylor, 2021). Any deviation from constant returns to scale is effectively forced into the farm size term so that the estimated farm size – TFP relationship includes any non-constant returns to scale. We use OLS to estimate the following production function:

$$y_{it} = \beta_0 + \boldsymbol{\beta} \boldsymbol{x}_{it} + \boldsymbol{\theta}_t + \boldsymbol{\gamma}_i + f(A_{it}) + \boldsymbol{\theta}_t \times f(A_{it}) + \varepsilon_{it} \qquad (1)$$

where y_{it} is the log of output per ha for farm i in year t, and x_{it} is the log of non-land inputs per ha: family labor, non-family labor, physical capital, draft animals, and purchased intermediate inputs. The variable of interest, $f(A_{it})$, is a measure of farm size, A_{it}, taking various functional forms including linear, quadratic, cubic, and a flexible dummy variable structure. Household-level fixed effects, $\boldsymbol{\gamma}_i$, imply that we identify the farm size – productivity relationship using within-household variation over time. We use survey year dummies, $\boldsymbol{\theta}_t$, and interact survey year with the measurement of farm size to allow the farm size – productivity relationship to vary over time. Omitting survey year interactions with inputs effectively assumes that the technology is time-invariant, forcing any changes in technology into the TFP term. The standard normal error term is given by ε_{it}, clustered at the household level, and observations are weighted by the expansion factors provided by MxFLS.

Additionally, a set of production functions are estimated that interact household explanatory variables with the measure of farm size. These models explore the potential for heterogeneity in the farm size-productivity relationship across important subgroups:

$$y_{ict} = \beta_0 + \boldsymbol{\beta x}_{ict} + \boldsymbol{\omega Z}_{ict} + \boldsymbol{\theta}_t + \boldsymbol{\gamma}_c + f(A_{ict}) + \boldsymbol{\theta}_t \times f(A_{ict}) + \boldsymbol{Z}_{ict} \times f(A_{ict}) + \varepsilon_{ict} \quad (2)$$

where y_{ict} is the log of output per ha for farm i in community c in year t, and the model uses community-level fixed effects, $\boldsymbol{\gamma}_c$, allowing for the inclusion of household-level explanatory variables, $\boldsymbol{Z}_{ict}$, and their interactions with farm size**.**

The second approach to exploring the farm size – productivity relationship estimates a stochastic production frontier. We adopt an output orientation, measuring technical inefficiency as the difference between what is actually produced by a farm, Y, and the maximum possible production given the inputs used by that farm, $f(\boldsymbol{X})$:

$$Technical\ Inefficiency = \frac{f(\boldsymbol{X})}{Y} \quad (3)$$

Rearrangement of the log of technical inefficiency generates the following relationship:

$$lnY = lnf(\boldsymbol{X}) - \ln(Technical\ Inefficiency) \quad (4)$$

Stochastic production frontier analysis differs from the estimation of an average production function because of the use of a two-part error term – a standard idiosyncratic error term, v, coupled with a one-sided error term, u, that measures inefficiency as deviations from the production frontier:

$$lnY = lnf(\boldsymbol{X}) + v - u \quad (5)$$

Stochastic frontier models allow for the simultaneous estimation of the frontier and heterogeneous inefficiency as a function of explanatory variables, and are estimated with maximum likelihood methods. We employ Greene's (2005) "true" fixed effects model with community-level fixed effects using the *sfpanel* command in Stata.[1] Working with community level fixed effects has the advantage of allowing the inclusion of household-level explanatory variables. Econometric

[1] See Belotti et al. (2012) for a discussion of *sfcross* and *sfpanel*.

estimation requires the assumption of a functional form for the frontier and distributional assumptions for v and u. A Cobb-Douglas functional form is assumed for the production frontier and the idiosyncratic component of the error term is assumed to follow a normal distribution, with standard errors clustered at the community level. A half-normal distribution is used for the inefficiency component of the error term, allowing for estimation of the variance of the inefficiency term simultaneously with the stochastic frontier.[2] More formally, the estimated model is given by:

$$y_{ict} = \beta_0 + \boldsymbol{\beta x}_{ict} + \boldsymbol{\omega Z}_{ict} + \boldsymbol{\theta}_t + \delta A_{ict} + \boldsymbol{\gamma}_c + v_{ict} - u_{ict} \quad (6)$$

$$v_{ict} \sim N(0, \sigma^2_{v,c}) \quad (7)$$

$$u_{ict} \sim N^+(0, \sigma^2_{u,ict}) \quad (8)$$

$$\sigma^2_{u,ict} = \alpha_0 + \alpha_1 A_{ict} + \boldsymbol{\theta}_t + \boldsymbol{\varphi V}_{ict} + \epsilon_{ict} \quad (9)$$

where $\boldsymbol{x}_{ict}$ are inputs per ha in logs, A_{ict} is log farm size, $\boldsymbol{Z}_{ict}$ and $\boldsymbol{V}_{ict}$ are vectors of household level controls used in the frontier and inefficiency equations, respectively, $\boldsymbol{\theta}_t$ are time dummies, $\boldsymbol{\gamma}_c$ are community dummies, v_{ict} is the standard normal idiosyncratic component of the error term, u_{ict} is the half normal inefficiency component of the error term, and ϵ_{ict} is a standard normal error term used in the inefficiency equation. For simplicity, we assume farm size (A_{ict}) enters linearly in the frontier model.[3]

III. Data

The Mexican Family Life Survey (MxFLS) is a longitudinal survey of Mexican households, representative of the Mexican population at the national, urban, and rural levels.[4] The MxFLS is a rich source of data for this analysis, as controlling for unobservable farm and community level characteristics using fixed effects is potentially important for determining the farm size – productivity relationship. Further, the decade long span of the surveys allows for a careful analysis

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[2] We attempted to estimate a frontier with a more flexible truncated normal distribution for the inefficiency term, allowing us to estimate its mean and/or variance (Wang, 2002). These models failed to converge with the MxFLS data.

[3] The results with farm size dummies are largely equivalent.

[4] MxFLS was designed, implemented, and is managed by the Iberoamerican University and the Center for Economic Research and Teaching (CIDE) in Mexico City, in conjunction with Duke University researchers. We thank Graciela Teruel at Ibero for her assistance and expertise in working with the Mexican Family Life Survey.

of how the size-productivity relationship has evolved in the wake of NAFTA and contemporaneous reforms affecting the Mexican agricultural sector.

The three survey rounds – 2002, 2005-06, and 2009-12[5] – tracked a broad range of individual, family, and community characteristics for the 8,437 initial households. The second (2005) and third (2009) waves of the survey successfully re-interviewed 90% and 94% of first wave households, respectively, with 83% of newly formed households in 2005 being re-interviewed in the third survey wave.

While not representative of the Mexican agricultural sector per se, the MxFLS is representative of both rural and non-rural Mexican households. As such, the use of the dataset to study Mexican agriculture has the important caveat that it underrepresents the larger, commercial agricultural operations to the degree that they are not family farms.[6] A comparison with the 2007 Agricultural Census reveals that both the census and MxFLS have less than 5% of farms that are greater than 50 ha. However, it is important to note that these "large" farms are not necessarily the same as those in the census because they are family-run farms and do not include corporate-run, commercial agricultural operations. However, the MxFLS over-represents farms less than 2 ha and under-represents farms between 20 ha and 50 ha relative to the 2007 census. While the MxFLS is not representative of the Mexican agricultural sector in its entirety, it is appropriate for studying household farms in Mexico.

We employ a farm (i.e. household) level analysis using all MxFLS households engaged in agricultural production. A plot-level analysis is not feasible because agricultural input data is recorded at the household level and is therefore not plot specific. However, as we are primarily concerned with documenting the farm size – productivity relationship in Mexico and how it has changed over time, and we are less concerned with fully explaining its determinants, a farm level analysis will suffice. Households in the MxFLS move in and out of agricultural production between survey waves. An unbalanced panel is constructed through two stages of restricting the MxFLS data: first, cross-sections of households with complete farm data are identified and cleaned

[5] The vast majority of third wave interviews, 95%, were conducted in 2009 and 2010.
[6] This is also true of the Mexico National Rural Household Survey (ENHRUM) used by Kagin et al. (2016), which is representative of rural communities in Mexico with between 500 and 2,500 inhabitants.

to eliminate outliers, and second, the unbalanced panel is formed out of all households that appear in two or more MxFLS survey waves.[7]

Table 1 shows all households using plots for agricultural production in a given survey wave referred to as agricultural households, whereas all households with plot size and output data for all non-fallow plots are referred to as complete farms. The number of farms in the panel includes the number of households with complete farm data in two or more of the survey years. These restrictions on the data leave us with a sample of 566 farms that appearing in two or more survey years.

Table 1: Agricultural Households and Complete Farms by Survey Year

	2002	2005	2009
N Households	8,440	8,437	10,119
N Agricultural Households	1,586	1,303	1,410
N Complete Farms	887	626	596
N Farms in Panel	483	412	359

*Note that *N Complete Farms* and *N Farms in Panel* are after trimming for outliers.

Input and Output Variables

Farms are classified into one of 7 farm size groups, as shown below in Table 2. The distribution of farms across these bins is roughly constant over time, although the share of farms between 0 and 0.5 ha is falling over time while the share of farms between 0.5 and 1 ha is increasing. More importantly, there is a considerable range in farm sizes in the sample, ranging from less than one hundredth of a hectare to 45,000 hectares. Mean farm size more than doubles between 2002 and the later survey waves, while the median fluctuates between 2.1 and 3.0. Approximately 75 percent of farms utilize only one plot for production in any given year.

[7] Some households have incomplete data on the size and/or output for one or more plots used in agricultural production in a given period, making the inclusion of these households in a farm-level analysis problematic. With inputs recorded at the household level and output and plot size data recorded at the plot level, the inclusion of farms with missing data on any plot used in production will introduce measurement error. After removing such households, we eliminate outliers by trimming the extremes of the farm size and land productivity distributions.

Table 2: Sample Size by Farm Size Group for Complete Farms

Farm Size Group	Panel		
	2002	2005	2009
0 to 0.5 ha	103 (21%)	66 (16%)	55 (15%)
0.5 to 1 ha	45 (9%)	60 (15%)	57 (16%)
1 to 2 ha	83 (17%)	75 (18%)	58 (16%)
2 to 5 ha	108 (22%)	88 (21%)	75 (21%)
5 to 10 ha	79 (16%)	76 (18%)	65 (18%)
10 to 20 ha	39 (8%)	23 (6%)	27 (8%)
> 20 ha	26 (5%)	24 (6%)	22 (6%)
Median Size (ha)	*2.5*	*2.1*	*3.0*
Mean Size (ha)	*101*	*232*	*218*
Total Farms	*483*	*412*	*359*

The preferred measure of agricultural output is a Fisher quantity index that includes all crop and livestock production for each farm in the MxFLS panel. Crop prices from the Food and Agriculture Organization of the United Nations are used to aggregate crop output. Together with a measure of the value of livestock production, an output index is constructed. The details are provided in Appendix 1 (available from the authors).

The MxFLS offers data on five agricultural inputs other than land: physical capital, draft animals, purchased intermediate inputs, family labor, and non-family labor. Physical capital and draft animals are measured as the value of household holdings, deflated to 2002 values. Purchased intermediate inputs are measured using reported expenditures on each of nine agricultural inputs over the course of the previous year, again deflated to 2002 values. An index of family labor is constructed using household members' time use and employment data in the MxFLS, and is an estimate of annual hours worked on the farm by all household members. In contrast, the non-family labor index is a measure of the number of non-household individuals that worked on each farm in each year, measured in workers and not labor hours. Detailed appendices are available from the authors documenting the construction of the quantity indices and the source and construction of the family labor and non-family labor indices. For all of the inputs there exist at least some, if not a majority, of households that have zeros for that input category, reflecting the range of agricultural modernization in the sample and substitutability between input categories. We follow Battese (1997) to estimate production functions with observations having zero inputs.[8]

Of principle importance is any relationship between inputs per hectare and farm size, as systematic relationships between input intensity and farm size potentially drive a wedge between the farm size – land productivity and farm size – total factor productivity relationships (Helfand and Taylor, 2021). We calculate the correlation coefficients between logged input per hectare and logged farm size for those farms with non-zero values of usage of each input. Conditional on using the input, the intensity (per hectare) of all inputs used declines with farm size, emphasizing the importance of moving from partial measures of productivity to a comprehensive measure such as TFP.

Additional Household Controls

A majority of plots are either privately owned property or are part of an *ejido* – a piece of communally held land where plots are farmed by designated households. It is commonly accepted that ejidos are less productive than privately held farms, although there is little empirical evidence comparing the TFP of these farms using micro data, so *ejido* status is controlled for. At least 91% of privately held plots in the MxFLS have some form of formal documentation in any given year, while just 75-84% of MxFLS ejido properties do. Documentation for privately held plots are typically more formal deeds or titles, whereas ejido plots primarily have a certificate of ejido status or agricultural rights, which are often not acceptable to private financial institutions for use as collateral. We control for both separately in the core empirical analysis.

In the first survey wave, 26% of panel farms are in Northern states where agriculture is characterized by having larger commercial farms with greater importance of the commercial production of maize. In comparison, 50% of first wave farms are in Southern and Central states where agriculture is characterized by more traditional, smallholder maize producers and the commercial production of fruits and edible vegetables (Prina, 2013). To capture these differences,

[8] For each input, k, for each farm in each survey year, we generate a dummy variable, D_{ict}, equaling 1 if there is zero input for that farm in that survey year and zero otherwise. We then define a new measure of the input, x^*_{ict}, equaling 0 if $D_{ict} = 1$ and the log of that input per ha (x_{ict}) otherwise. The inclusion of the dummy variables and newly constructed inputs allows for unbiased estimation of the production function's parameters in the presence of zeros while using the full sample.

we introduce regional interactions with farm size in estimations of equation (2), allowing the farm size – TFP relationship to vary across the differing agricultural regions.

Additional household level controls are grouped into two broad categories: demographic variables that are largely exogenous, including head of household's age, education, gender, indigenous status, and primary language spoken, and variables describing agricultural practices that are mostly endogenous, including dummies for subsistence farming practices, monocropping, access to formal lines of credit, and participation in the government's agricultural support programs *Procampo* and *Alianza*. While potentially endogenous, these controls are introduced in the community fixed effects models to shed light on potential channels affecting TFP and the farm size – TFP relationship. To account for potentially persistent negative productivity shocks we generate a dummy variables for whether the household suffered crop or livestock loss in either of the previous two years before each survey wave.

IV. Empirical Results

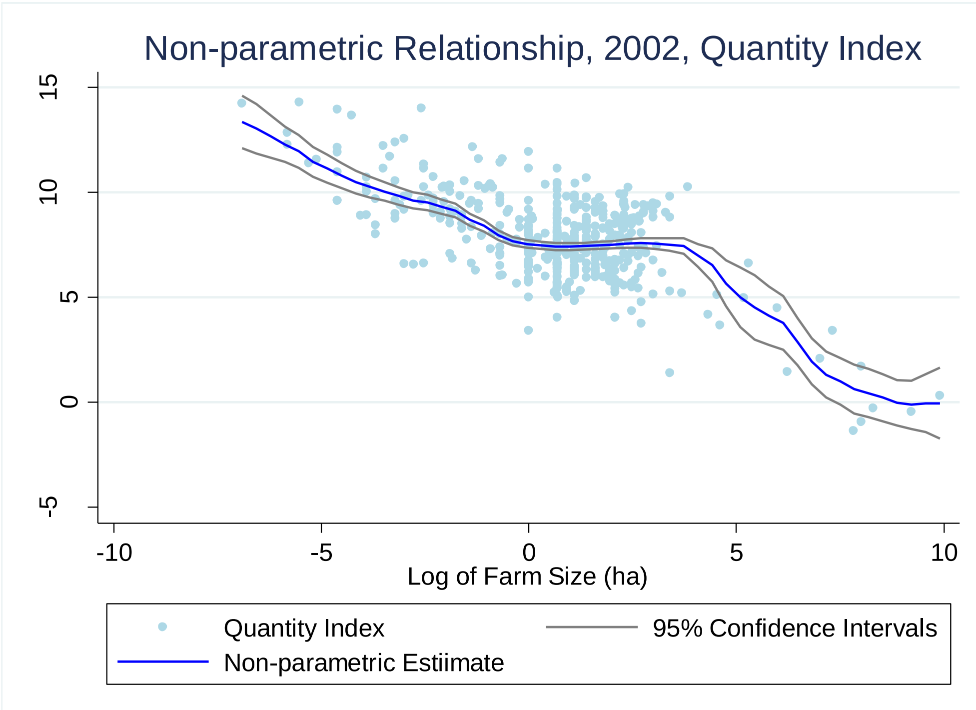
As with much of the literature, we begin the discussion of the farm size – productivity relationship using land productivity, measured as output per hectare. Figure 1 shows the non-parametric relationship between the log of farm size and the log of output per hectare in 2002, where output is measured using the Fisher quantity index.[9] There is a clear inverse relationship between farm size and land productivity over the entire range of farm sizes, and while not shown here this relationship is strikingly consistent across the three survey waves. Land productivity falls rapidly up to approximately 1 ha, at which point the relationship levels before resuming a dramatic decline in land productivity after approximately 20 ha.

Production Function Analysis

As discussed in Helfand and Taylor (2021), an inverse relationship between farm size and land productivity is neither necessary nor sufficient for the existence of an inverse relationship between farm size and total factor productivity. For reference, the linear relationship between land productivity and farm size is estimated. Column 1 of Table 3 shows that farm size is inversely related to land productivity at the 1% level of significance, where we estimate the elasticity of land productivity with respect to farm size to be -0.85. We then estimate the average production

[9] Estimated using the default local polynomial regression in Stata.

Figure 1: Non-parametric Relationship between Farm Size and Productivity, 2002



function specified in equation (1) assuming four alternate specifications of the farm size – productivity relationship that vary in their flexibility. These regressions measure output using the quantity index, weight observations by the expansion factors provided by MxFLS, use the preferred measure of the family labor index, employ household fixed effects, and cluster standard errors at the household level. Coefficients for the farm size variables, the primary variables of interest, are displayed in Table 3. The technology coefficients from these regressions are available upon request.

The results indicate an inverse relationship between farm size and TFP, as shown by the negative and statistically significant coefficient on the linear Farm Size variable in model 2. In the sample, a 1% increase in farms size is associated with a 0.82% decrease in output per hectare, *ceteris paribus*. These coefficients on farm size are slightly less negative than in model 1, but not statistically different, indicating that the relationships between farm size and land productivity and farm size and TFP are almost identical in this sample.

Models 3 and 4 allow for a quadratic and cubic relationship between farm size and TFP, but the coefficients on the higher ordered terms are either not statistically significant or do not have a noticeable impact on the linear model. Model 5 captures some non-linearity in the farm size – TFP relationship by using dummy variables for 7 farm size bins. The smallest of farms, those less than one half of a hectare, are significantly more productive than all other farms, while the largest, those greater than 20 hectares, are significantly less productive than all smaller farms. Productivity between these two extremes, however, appears relatively stable. This closely mirrors the non-parametric relationships between farm size and land productivity shown in Figure 1, highlighting the need to assume a flexible functional form to fully understand the farm size – productivity relationship. The parametric specifications 2 through 4 do not capture these subtleties.

We see little change in the inverse relationship over time across all models, as none of the farm size and survey year interaction terms (not shown in Table 3) are statistically significant. The finding of a time invariant inverse relationship between farm size and productivity – when using both land productivity and TFP – suggests that the IR is alive and well in Mexico. There is, however, evidence for a decline in average productivity over time in this sample, as the 2009 dummy variable is negative and statistically significant in most of the models.

Model 6 uses a linear specification for farm size, differing from model 2 by using community fixed effects and a set of household explanatory variables (not included in the table). Model 6 indicates that monocropping and operating as a subsistence farm have a consistently negatively relationship with TFP. In contrast, participating in Procampo is positively associated with productivity. Having more education is positively related to TFP, although with the exception of a college education these impacts are not all statistically significant at standard levels. It is important to reiterate that these are potentially endogenous explanatory variables, and we should not interpret the coefficients as identifying causal relationships. A comparison of models 2 and 6, however, indicates that the inclusion of these potentially endogenous variables does not appear to bias the estimates of the farm size – productivity relationship, our coefficient of interest.

Table 3: Farm Size Coefficients

	(1) Linear w/o Inputs	(2) Linear Model 1	(3) Quadratic	(4) Cubic	(5) Dummies	(6) Linear Model 2
Farm Size	-0.854***	-0.821***	-0.808***	-0.773***		-0.814***
	(0.076)	(0.103)	(0.099)	(0.143)		(0.068)
Farm Size^2			-0.012	-0.007		
			(0.016)	(0.020)		
Farm Size^3				-0.001		
				(0.004)		
0.5 to 1 ha					-1.779***	
					(0.636)	
1 to 2 ha					-2.382***	
					(0.576)	
2 to 5 ha					-2.072***	
					(0.587)	
5 to 10 ha					-2.848***	
					(0.741)	
10 to 20 ha					-2.247**	
					(1.055)	
20+ ha					-6.151***	
					(1.355)	
2005 Dummy	-0.315	-0.243	-0.281	-0.292	-0.160	-0.208
	(0.200)	(0.176)	(0.187)	(0.218)	(0.450)	(0.158)
2009 Dummy	-0.486**	-0.381*	-0.465**	-0.445*	0.133	-0.551***
	(0.226)	(0.211)	(0.221)	(0.267)	(0.632)	(0.121)
Constant	9.626***	11.561***	11.672***	11.601***	11.292***	9.289***
	(0.307)	(2.034)	(1.924)	(1.958)	(2.681)	(1.067)
Inputs	No	Yes	Yes	Yes	Yes	Yes
Year – Farm Size Interactions	Yes	Yes	Yes	Yes	Yes	Yes
Community FE and HH Variables	No	No	No	No	No	Yes
R^2	0.85	0.86	0.86	0.86	0.85	0.72
N	1235	1235	1235	1235	1235	1235

Standard errors in parentheses: * p<0.10, ** p<0.05, *** p<0.01

Table 4: Community Fixed Effects with Household Control Interactions

	(1) North	(2) Procampo	(3) Monocrop	(4) Subsistence	(5) Higher Education	(6) Ejido	(7) Deed/Title	(8) Ag. Rights Certificate	(9) Access to Credit
Farm Size	-0.813***	-0.841***	-0.819***	-0.816***	-0.812***	-0.820***	-0.805***	-0.815***	-0.814***
	(0.067)	(0.076)	(0.090)	(0.081)	(0.069)	(0.076)	(0.073)	(0.076)	(0.069)
Farm Size*North	-0.013								
	(0.196)								
Farm Size*Procampo		0.090							
		(0.068)							
Farm Size*Monocrop			0.009						
			(0.074)						
Farm Size*Subsistence				0.004					
				(0.057)					
Farm Size *Education					-0.038				
					(0.083)				
Farm Size*Ejido						0.025			
						(0.069)			
Farm Size*Deed							-0.016		
							(0.047)		
Farm Size*Certificate								0.004	
								(0.055)	
Farm Size*Credit									0.016
									(0.078)
2005 Dummy	-0.208	-0.214	-0.208	-0.209	-0.209	-0.199	-0.203	-0.207	-0.208
	(0.158)	(0.157)	(0.160)	(0.157)	(0.158)	(0.166)	(0.157)	(0.163)	(0.158)
2009 Dummy	-0.550***	-0.575***	-0.553***	-0.551***	-0.555***	-0.548***	-0.548***	-0.550***	-0.550***
	(0.121)	(0.125)	(0.115)	(0.121)	(0.121)	(0.121)	(0.120)	(0.125)	(0.122)
Community FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
N	1235	1235	1235	1235	1235	1235	1235	1235	1235

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.01

Estimates of equation (2) explore heterogeneity in the farm size – productivity relationship across different groups of Mexican family farms by interacting indicator variables for those groups with farm size. For simplicity, we assume the farm size – TFP relationship to be linear and time invariant.[10] Table 4 displays the results from interacting farm size with being located in the more commercially oriented agricultural region of Northern Mexico, participation in Procampo, practicing monocropping, operating as a subsistence farm, and whether or not the household head has any education beyond secondary school. Farm size is further interacted with controls for ejido status, various forms of property rights, and access to credit, variables of special interest given recent reforms of the ejido system and rural credit markets. Overall, the farm size – TFP relationship remains stable, as none of these additional interactions contribute to explaining the farm size – TFP relationship that we have identified.[11]

Robustness Tests

We subject the estimated farm-size – TFP relationship to a series of robustness tests using linear specifications (2) and (6) from Table 3. The results are shown in Table 5. Model 1 tests the sensitivity of the relationship to decisions regarding the construction of the family labor index by using an alternative index of family labor. In model 2, we test the impact of choice of weighting of the observations. Whereas the core results apply the MxFLS weights designed to make the sample statistically representative of Mexican households in each survey year, model 2 shows results when we apply no weighting at all. We explore sensitivity to the use of weights because (a) we are interested in Mexican agriculture, not rural Mexican households, and (b) the treatment of the data reduces the sample size; therefore, it is not clear that these weights remain appropriate. Next, model 3 uses an alternative measure of the dependent variable – farm output. Whereas the core results use the preferred quantity index for each household, model 3 deflates the nominal value of production in each year for each household and uses the real value of output (in 2002 Mexican pesos). Lastly, model 4 uses the real value of output as in model 3, but estimates the relationship over the repeated cross-sections, speaking to the potential bias induced by households selecting into or out of the unbalanced panel.

[10] Relaxing the assumption of a linear relationship does not qualitatively alter the results presented here.
[11] In addition, we estimate separate regional models using household fixed effects, resulting in the same conclusion of a homogenous farm size – TFP relationship across regions.

Overall, these alternative treatments of the data generate qualitatively similar results to the core regressions in Table 3 for our primary variables of interest. This is true in terms of the coefficient signs and orders of magnitude. The consistency across models is reassuring that treatment of the data is not driving the core results regarding the farm size – TFP relationship.[12] In similar fashion, estimated coefficients on household explanatory variables are quite robust.

Table 5: Farm Size Coefficients, Linear Robustness Checks

	(1) Alt. Labor Index	(2) No Weights	(3) Alt. Output	(4) Alt. Output Cross Section
Farm Size	-0.668***	-0.818***	-0.825***	-0.668***
	(0.148)	(0.076)	(0.103)	(0.060)
2005 Dummy	-0.262	-0.196	-0.335*	-0.313**
	(0.181)	(0.141)	(0.175)	(0.126)
2009 Dummy	-0.418*	-0.336**	-0.176	-0.380***
	(0.217)	(0.169)	(0.210)	(0.126)
2005* Farm Size	0.072	0.064	0.089	-0.030
	(0.087)	(0.063)	(0.090)	(0.037)
2009* Farm Size	-0.108	-0.013	-0.109	-0.084
	(0.121)	(0.080)	(0.117)	(0.052)
Constant	11.509***	10.032***	11.593***	7.042***
	(1.923)	(1.307)	(2.035)	(1.160)
Household FE	Yes	Yes	Yes	No
Community FE	No	No	No	Yes
R^2	0.86	0.81	0.86	0.68
N	1235	1235	1235	2090

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.01

Frontier Analysis

Estimating a stochastic frontier complements analysis of the average production function by identifying productivity at the frontier and production inefficiencies. Together, these components determine average TFP identified with the average production function. Whereas the estimation of the average production function allows us to assess the relationship between farm size and average productivity, stochastic frontier analysis allows us to assess any relationships

[12] In results not shown here, we estimate the core models using crop production only in measuring output and the conclusions regarding the farm size – productivity relationship are robust to this dimension as well.

between farm size and productivity at the technical frontier and between farm size and technical inefficiency.

The results of three specifications of the stochastic production frontier are shown in Table 6, with the top and bottom panels displaying the results from the frontier and variance of inefficiency equations, respectively. Model 1, the baseline model, has no additional household controls in either the frontier ($\mathbf{Z}$) or the inefficiency equations ($\boldsymbol{W}$). Model 2 includes dummy variables for the household head's level of education in the frontier equation and includes a dummy variable for the household head being of indigenous ethnicity in the inefficiency equation. Model 3 includes education in the frontier equation, adding interaction terms between farm size and the survey year dummies in both the frontier and the inefficiency equations. The models all use community fixed effects and, for simplicity, have farm size entering linearly.

The estimated coefficients from models 1 – 3 are largely consistent. They indicate a strong inverse relationship between farm size and frontier TFP and that the frontier is increasing over time, reflecting positive technical change. The coefficients on inputs are positive and stable across specifications, with family labor and purchased intermediate inputs being significant. The variance of the inefficiency term σ_u^2 is roughly double the size of the variance of the noise σ_v^2 in all models, and lambda – the ratio of the two variances – indicates that estimation of a stochastic frontier is appropriate with the MxFLS data.[13]

The models indicate an inverse relationship between farm size and productivity at the technological frontier of the same order of magnitude as the farm size-TFP relationship estimated in the preceding analysis of the average production function. The coefficients on survey year dummies in Table 6 are all positive and significant, indicating that the frontier is increasing over time. Thus, in contrast to the results from the average production function analysis where evidence of declining average TFP over time was found, here we find evidence of positive technical change at the frontier. The interaction between farm size and the survey year dummies in model 3 identifies a positive and significant relationship between farm size and technical change,

[13] In models estimated with a constant variance of the inefficiency distribution (σ_u^2), and thus no explanatory variables, Stata provides a p-value for the test of lambda equal to zero. This hypothesis is rejected at greater than the 1% level of significance, providing evidence in support of the stochastic frontier model.

suggesting that technical change has been biased towards larger farms and that the inverse relationship along the frontier became less steep over time.

Models 1 and 2 show that, while the variance of the inefficiency distribution increased over time, there is no relationship between farm size and inefficiency. The inclusion of interactions between farm size and survey year dummy variables in model 3, however, reveals a more nuanced dynamic relationship between farm size and technical inefficiency. Larger farms were indeed more efficient than smaller farms in 2002 (i.e. they operated closer to the frontier) but inefficiency is increasing faster for larger farms. These differential changes in inefficiency across the farm size distribution have caused the farm size - inefficiency relationship to disappear in the latter waves of the MxFLS.[14] Model 3 reveals that rising technical inefficiency has accompanied technological change, suggesting that the majority of farms have been unable to keep up with the TFP growth of the most productive farms. This is particularly true for larger farms, who have experienced faster growth in both frontier productivity and technical inefficiency.

In models not shown here, we estimate a stochastic frontier including dummy variables for education in the inefficiency term, and also for the full set of household controls from model 7 in Table 3. Having secondary or college education reduces the variance of the one-sided inefficiency term when education is included in the inefficiency equation. In addition to educational attainment of the household head, technical inefficiency is lower among Procampo participants and higher among farms practicing monocropping. When interacted with farm size, none of the interaction terms are statistically significant, suggesting that they do not fundamentally change the relationships observed in Table 6.

[14] This can be seen by adding the farm size coefficient (-0.32) in model 3 with the year*size interaction from 2005 (0.37) or 2009 (0.42). In either case, the sum of the two coefficients is not statistically significantly different from zero.

Table 6: Stochastic Frontier Production Function Results

	(1)	(2)	(3)
Frontier Equation			
Farm Size	-0.642***	-0.653***	-0.805***
	(0.051)	(0.050)	(0.062)
2005 Dummy	0.477**	0.475**	0.400**
	(0.186)	(0.177)	(0.201)
2009 Dummy	0.790***	0.799***	0.711***
	(0.212)	(0.207)	(0.223)
2005*Farm Size			0.192***
			(0.064)
2009*Farm Size			0.204*
			(0.108)
Family Labor	0.077**	0.077**	0.068**
	(0.032)	(0.033)	(0.033)
Physical Capital	0.008	0.012	0.037
	(0.047)	(0.042)	(0.046)
Draft Animals	0.028	0.026	0.006
	(0.034)	(0.032)	(0.030)
Purchased Intermediates	0.148***	0.139***	0.145***
	(0.038)	(0.038)	(0.041)
Non-family Labor	0.045	0.041	0.024
	(0.034)	(0.034)	(0.033)
Inefficiency Equation			
Farm Size	0.037	0.031	-0.317***
	(0.062)	(0.060)	(0.119)
2005 Dummy	1.152***	1.163***	1.198***
	(0.377)	(0.361)	(0.430)
2009 Dummy	1.838***	1.878***	1.870***
	(0.407)	(0.387)	(0.401)
2005*Farm Size			0.368**
			(0.149)
2009*Farm Size			0.417**
			(0.167)
$E(\sigma_u^2)$	1.679	1.666	1.620
σ_u^2	0.846	0.840	0.853
λ	1.985	1.983	1.899
N	1235	1235	1235
Education Controls in Frontier	No	Yes	Yes

Standard errors in parentheses
** p<0.10, ** p<0.05, *** p<0.01*

Discussion

The analysis of the MxFLS data indicates an inverse and time-invariant relationship between farm size and TFP. Underlying this IR is a negative relationship between farm size and frontier productivity that has diminished over time and a positive relationship between farm size and technical efficiency that disappeared over the sample period. This evidence suggests that, in the wake of NAFTA era reforms, the IR is weakening for the most productive farms along the production frontier but that this change is not widespread. Although frontier productivity is increasing most rapidly for larger farms, the higher growth of inefficiency for large farms leaves the average farm size – TFP relationship unchanged over the period. The evolving relationships between farm size and frontier productivity and technical efficiency cast doubt on the ability to exploit the existing inverse relationship between farm size and TFP to generate productivity gains.

These results are complemented by previous work on the farm size – productivity relationship in Brazil. Whereas the Brazilian experience suggests a dynamic farm size – TFP relationship, with an inverse relationship in traditional agriculture becoming flat and potentially positive with modernization, we observe no such dynamics in the Mexican sample. It is quite similar, however, to the more traditional agricultural regions in Brazil that display a persistent inverse relationship between farm size and TFP. The lack of corporate-run commercial farms is one limitation of using the MxFLS data, inhibiting analysis of the farm size-productivity relationship across all types of Mexican agriculture. This is especially true in light of findings that, in Brazil, larger commercial farms (along with the smallest of family farms) exhibit distinct advantages in achieving productivity growth (Rada et al., 2019).

The frontier analysis using MxFLS data finds that technical change has been biased towards larger farms, weakening the farm size – productivity relationship at the frontier and indicating the average inverse relationship between farm size and productivity would have weakened with modernization of the agricultural sector in the absence of inefficiency growth. Larger farms are potentially the key drivers of future productivity growth in Mexico. While policies geared towards smaller family farms may not have large returns in terms of increasing overall agricultural productivity, they are likely very important for poverty reduction. Even if small farms generate an increasingly smaller share of agricultural output, their roles in generating livelihoods for rural households mean they are likely here to stay. Increasing smallholder productivity remains an important component of facilitating poverty reduction in rural communities.

These findings are largely consistent with earlier empirical work by Kagin et al. (2016), who estimate both an average production function and a stochastic production frontier using a different panel of Mexican family farms. They find that both technical change and technical inefficiency increased over time and, as with the current analysis, their fixed effects estimates show inverse relationships between farm size and both TFP and frontier productivity. Similarly, they find that smaller farms are more efficient than larger farms. In addition to highlighting the non-linearity in the farm size – TFP relationship, we provide evidence of a more nuanced and dynamic relationship between farm size and technical inefficiency and between farm size and productivity at the frontier. Larger farms have both more rapidly growing frontier productivity and technical inefficiency than their smaller counterparts, and these are important for policy considerations.

We find evidence of declining average TFP over the period of analysis for the MxFLS sample of family farms. This appears to be driven by increasing average technical inefficiency offsetting the positive technical change and expansion of the productivity frontier. The largest farms in the sample and their relatively rapidly growing technical inefficiency are an important factor here, indicating a growing advantage for some larger farms in harnessing more modern agricultural practices that has not been widespread enough to translate into sector-wide average TFP growth. Policies enabling broader inclusion in the benefits from technical change would both increase average TFP and likely further diminish the IR. Whereas policies promoting technical change are more relevant for smaller farms, policies improving technical efficiency, such as extension services, are exceptionally important for larger farms. The growing technical inefficiency observed in Mexico indicates the potential for policies designed to promote and support the adoption and efficient use of best practices to achieve gains in agricultural productivity.

Declining average TFP over time is a curious result, running counter to the body of long-run country-level analyses and the micro-level analysis of Kagin et al. (2016). One important caveat is the MxFLS sample does not include corporate run commercial farms as do national-level studies utilizing the agricultural census. To the extent that such farms have more effectively harnessed the gains from technological change the potentially heightened productivity of such large farms is not included in the current evaluation of the farm size – TFP relationship in Mexican agriculture or growth in average TFP over time. This has important policy implications for the development impacts of agriculture productivity gains – if these gains are experienced primarily by corporate-run commercial farms and not by family-run farms, the potential impacts on poverty and broader rural economic development will not be fully realized. Productivity gains for smaller family farms not only reduce poverty directly but are also likely to contribute more to local development because of how they interact with the local economy. To be effective, policy directed at spurring development and poverty reduction through agricultural productivity gains should be inclusive of smaller family farms.

Participation in Procampo and increased education are found to be positively associated with the agricultural productivity of Mexican family farms, whereas the practices of monocropping and operating as a subsistence farm are found to be negatively related with TFP. We are tentative in drawing stronger conclusions about the causal impact of these variables, as they are likely endogenous. However, the frontier analysis suggests how these controls relate to productivity. Education appears to increase the efficiency with which inputs are used on family farms, and monocropping is found to be an inefficient use of inputs. In this light, farmer education – particularly in methods such as intercropping – is expected to increase technical efficiency on family farms. Procampo is primarily an income support program, and it is unclear how participation would affect agricultural productivity. On the one hand, participation may relax income constraints and allow for adopting more productive methods because payments are distributed prior to the planting season. This would suggest an emphasis on improving access to credit to improve the efficiency of Mexico's family farms. On the other hand, the historical production requirements of Procampo participation may mean that participants are simply more experienced producers.

A significant share of farms do not have formal documentation of property rights. Policies to ensure that farms have the necessary documentation could potentially help provide farms with the opportunity to keep abreast of technical change, as documented property rights are an important condition for accessing credit and thus facilitating adoption. Nevertheless, we find no relationship here between agricultural TFP and property right documentation, access to credit, or ejido status, as we would have expected.

V. Conclusions

Working with a sample of family farms from the Mexican Family Life Survey (MxFLS), we document a persistent inverse relationship between farm size and land productivity over the period 2002 to 2009. Similarly, when estimating an average production function we find a time-invariant inverse relationship between farm size and TFP, driven by the relatively high productivity of the smallest farms relative to those in the middle, and relatively low productivity of the largest farms. This is complemented by a stochastic frontier analysis, allowing for estimation of the relationship between farm size and frontier productivity and between farm size and technical inefficiency. Analysis of the production frontier reveals a dynamic inverse relationship between farm size and frontier productivity, where technical change has increased the frontier for larger farms at a faster rate than for smaller farms, weakening the inverse relationship along the frontier of productivity. Despite these changes at the frontier, the farm size – average TFP relationship has remained constant due to technical inefficiencies growing faster for larger rather than smaller farms. In essence, many of the larger farms were not able to keep up with technical change at the frontier, suggesting that successfully reducing technical inefficiency for this group could mediate, if not reverse, the farm size - productivity relationship.

To the extent that the inverse relationship between farm size and TFP has flattened along the frontier for Mexican family farms, it suggests that size may fade as one of the key determinants of productivity differences as agricultural sectors modernize. Policies that help family farms keep abreast of improvements in agricultural technology, such as education and extension, will be needed to reduce growing technical inefficiency. These findings support the claim that family farms have struggled in the wake of NAFTA era market liberalization, and we echo the calls of Pérez et al. (2008) that investment in rural infrastructure and assistance for smallholder transition into niche markets would support productivity growth for family farms.

Robust agricultural TFP growth is also important for poverty reduction. By growing food supply more rapidly than demand, falling prices benefit poor consumers wherever they may live. And for the small farms that continue to exist, either because they are competitive or because they have few other opportunities, TFP growth helps to boost income. Where farms are too small, as in many parts of Mexico, increased productivity may still be insufficient to lift households out of poverty. Households in regions with access to non-agricultural employment may persist, and some will escape poverty, but migration is likely to continue. An important extension of this work would assess the potential impact of productivity growth on poverty alleviation and rural economic development.

An important limitation of the analysis conducted here is the absence of non-family commercial farms in the MxFLS sample. Future research should extend this analysis to a nationally representative sample of farms, such as the Mexican Agricultural Census, which would include family and non-family agricultural operations. Extending the analysis to the entire range of farm sizes and farm types would allow for a more complete analysis of the farm size – productivity relationship. Such an extension could provide a more comprehensive contribution to policy efforts to increase agricultural productivity and reduce rural poverty.

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