Are There Too Many Farms in the World? Labor-Market Transaction Costs, Machine Capacities and Optimal Farm Size

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November 7, 2017

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Agricultural Productivity

- There are substantial differences in agricultural productivity across countries
- Important for development
  - Persistent large gaps between agricultural and other sectors in terms of earnings.
  - A large fraction of poor households have some share of income in agriculture.
- There are is also substantial variance in productivity within communities
  - But evidence suggests that technology diffusion of profitable technologies in low-income agriculture is relatively rapid
  - Are productivity differences just a matter of fixed factors like land quality or do they reflect deeper issues?

Productivity and Scale

- One important predictor of differences in productivity within communities is farm scale.
- But relationship is not uniform
  - Across countries large farms are more productive
  - Within rich countries large farms are more productive
  - Within poor countries small farms are more productive
- Is it really plausible that there are scale dis-economies in farming in low-income countries?
- If so, why?

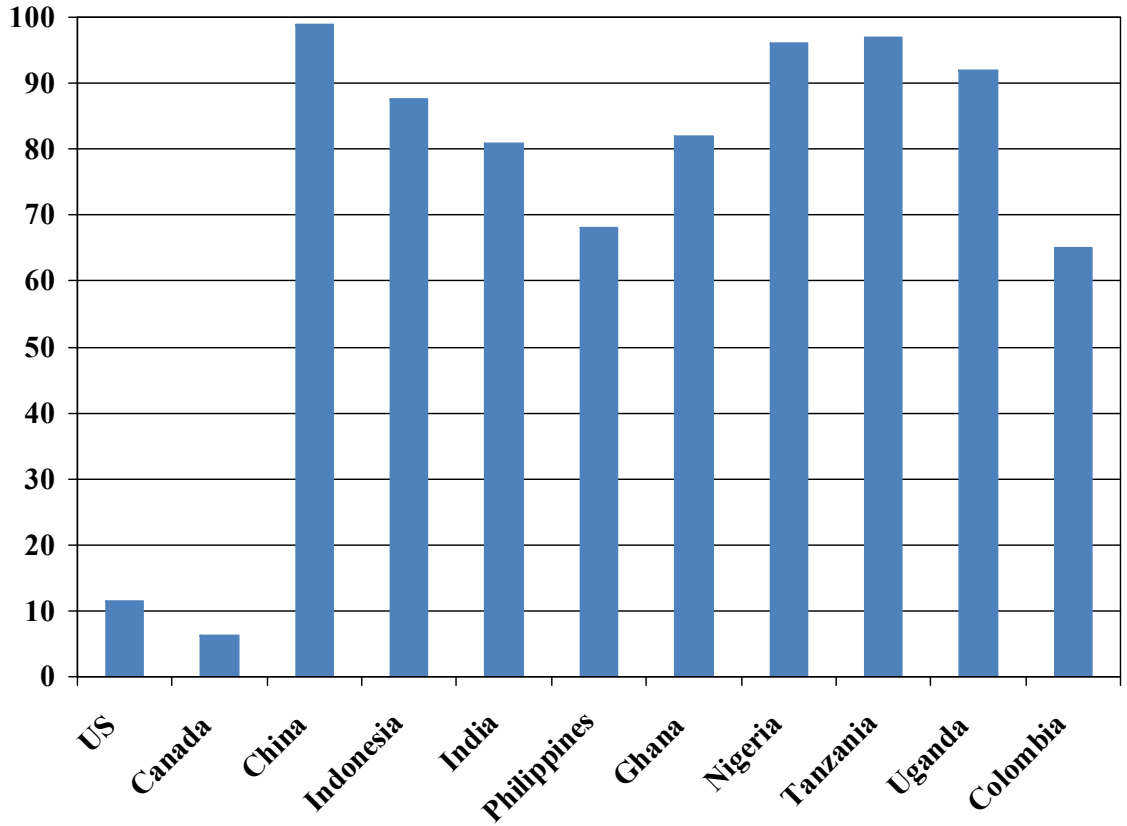
Implications of Land Scale

The question of farm size is a big and old question for development

- Low-income countries are characterized by very small farms compared with developed countries.
- Is changing farm scale critical to development?
- What are the consequences of land reform or privatization schemes?
- What is the justification, if any, for "land ceiling" and "land consolidation" schemes?
- Are there constraints faced by small farmers such as credit, marketing or technology access that, if released through policy, would increase incomes of rural farmers?
- Does changing the scale of operation substantially change agricultural labor and labor productivity?
- If so how does this affect rural poverty?

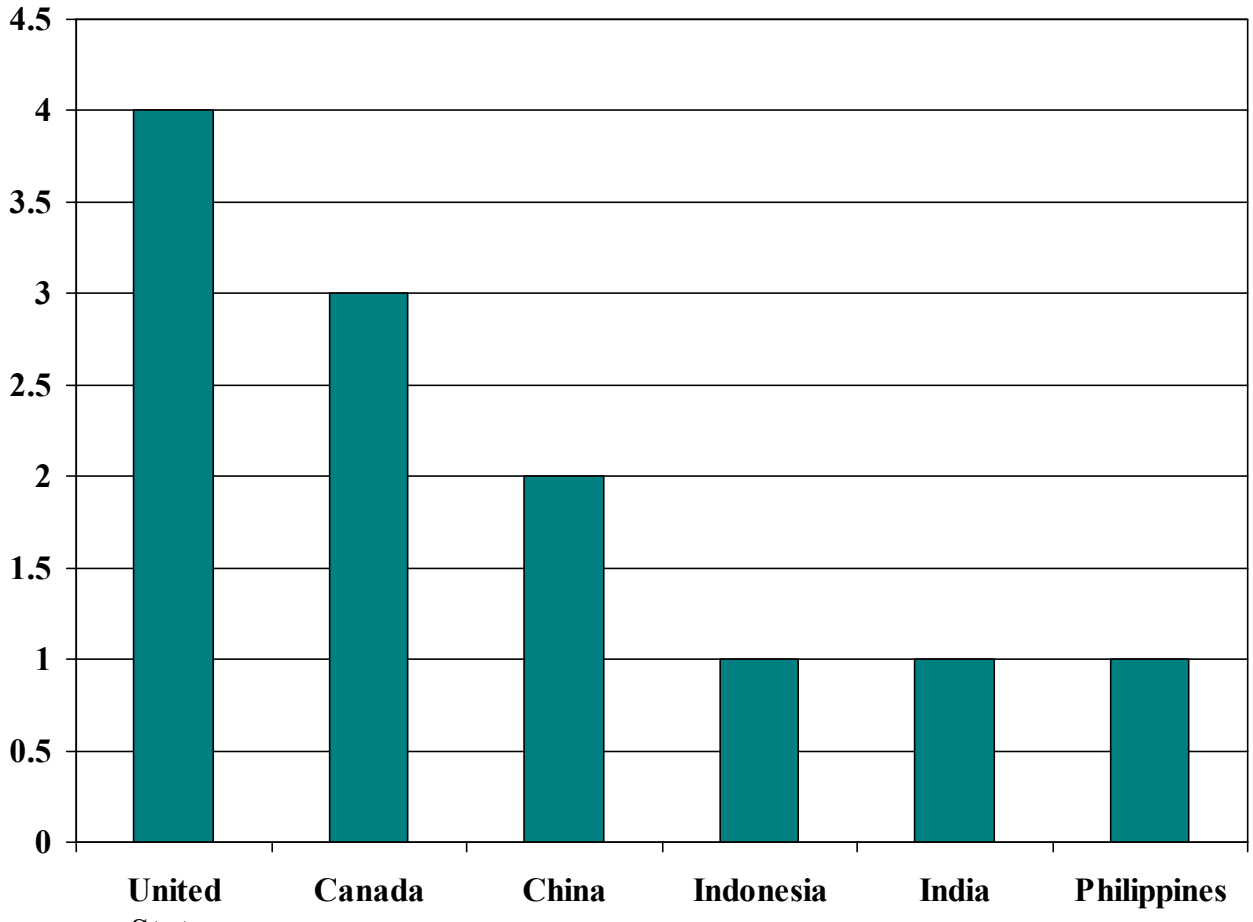
Percent Small Farms by Country

Figure 1. Percent of Households with Operational Landholdings Below 10 Acres, by Country



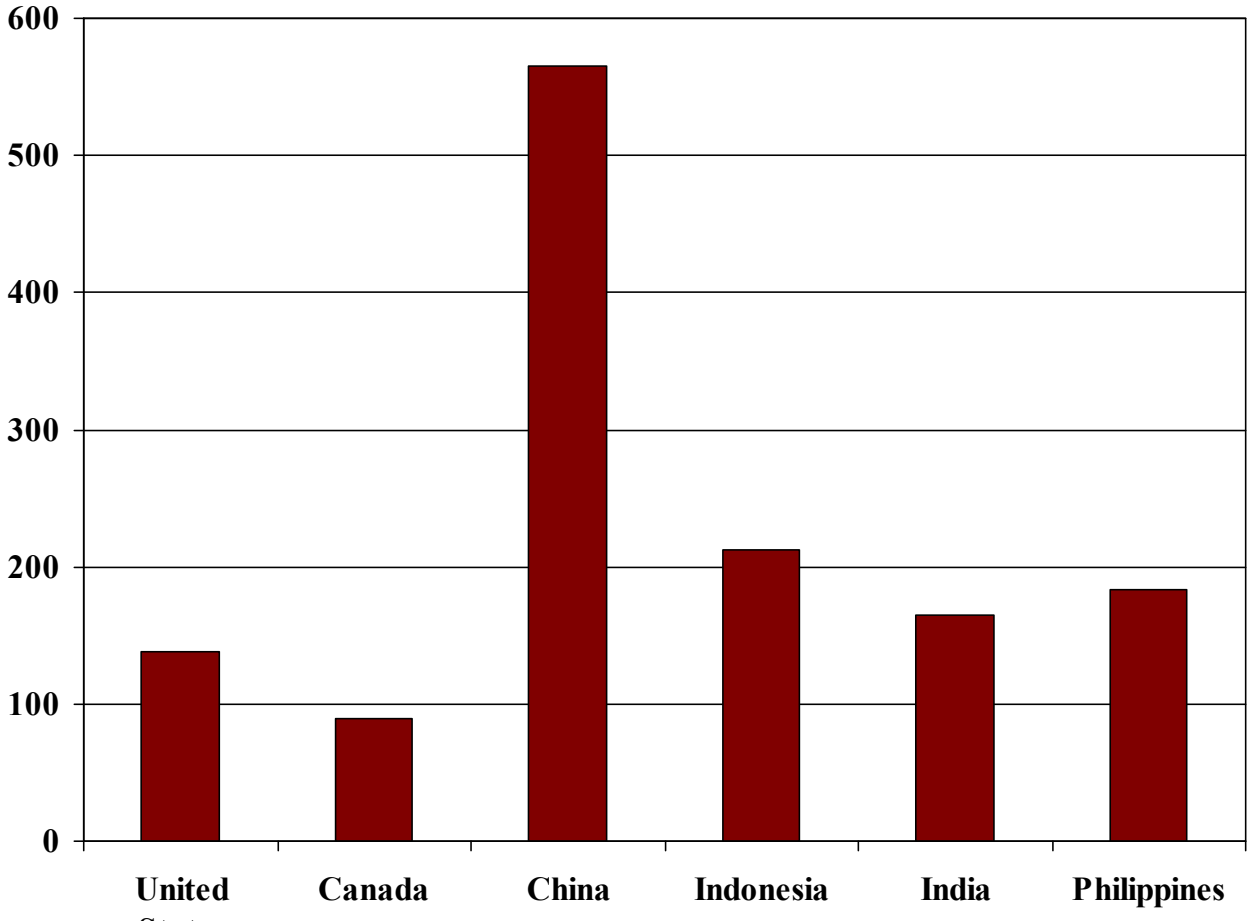
Yields by Country

Figure 2. Soybean Yields (Metric Tons per Hectare) in 2016, by Country (Source: USDA, 2016)



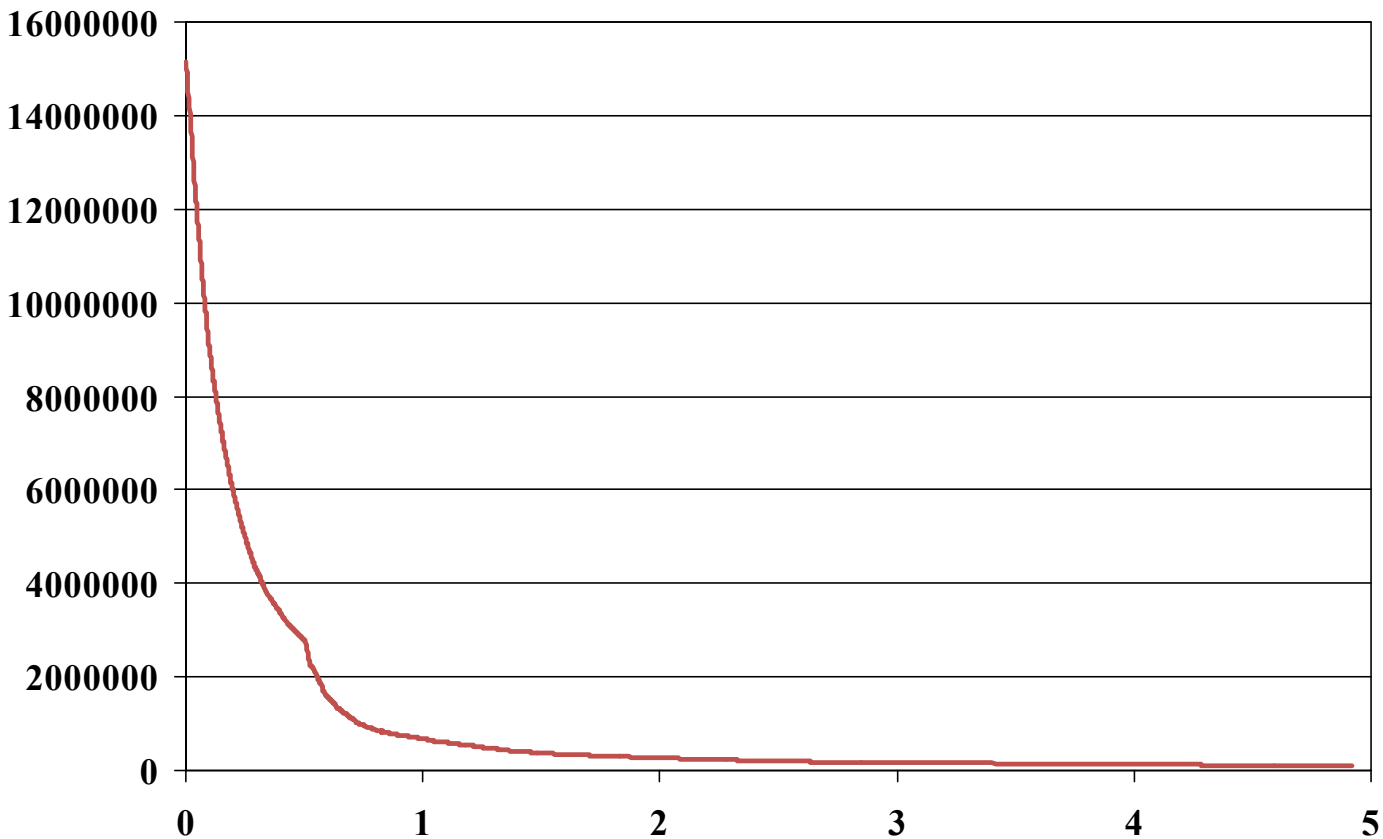
Fertilizer by Country

Figure 3. Fertilizer Intensity (Kilograms per Hectare) in 2014, by Country (Source: World Bank, 2016)



Plot Value and Acres (Nigeria)

Figure 4. Relationship Between Plot Value per Acre (Nigerian Naira) and GPS-Measured Plot Size (Acres) (Nigeria General Household Panel, 2015-16)



Challenges

Challenges to Identifying Scale Economies

- Span of the distribution of plot/land sizes limited in most low-income countries - you simply cannot observe productivity of large farms.
- Plot size, plot quality and farmer ability may be correlated.
- Plot size may be measured with error and that error may be correlated with plot size.
- The land allocation process may be endogenous (see 2 above).

Mechanisms

Challenges to Identifying Why there are Scale Economies

- Need a model of input markets, farmer behavior.
- Need information on all input costs to calculate returns on land (profits).
- Need information on the unit prices paid per operation and quantities used by input type.
- Need price schedules by quantity hired by input type and capacity.
- Need information on the productivity-relevant characteristics of equipment used: capacity (e.g, horsepower, work accomplished by acreage).

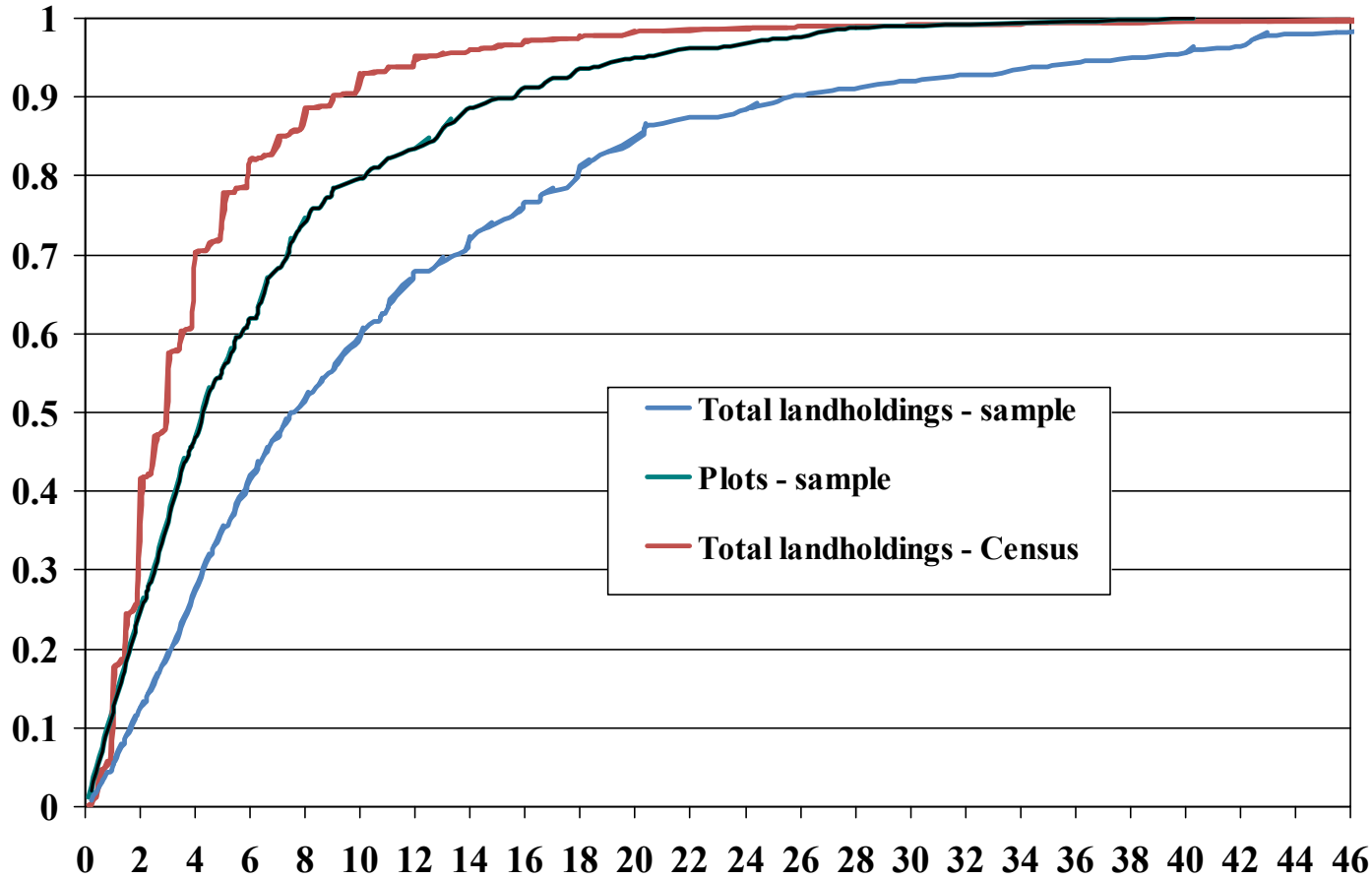
Data

ICRISAT India VLS data set

- 6-year panel of farmers at the plot level, 2009-2014
- 20 villages
- in 6 states
- 819 farmers
- 2,015 plots
- Complete census of all households in the villages.
- Sampling of survey stratified by farm size, so over-sampling of larger farms. Four equal-sized groups: none, small, medium, large

Land Distribution ICRISAT VLS

Figure 5. Cumulative Distributions of Owned Total Land and Land Plots (Acres), By Sample and Census: ICRISAT VLS 2014



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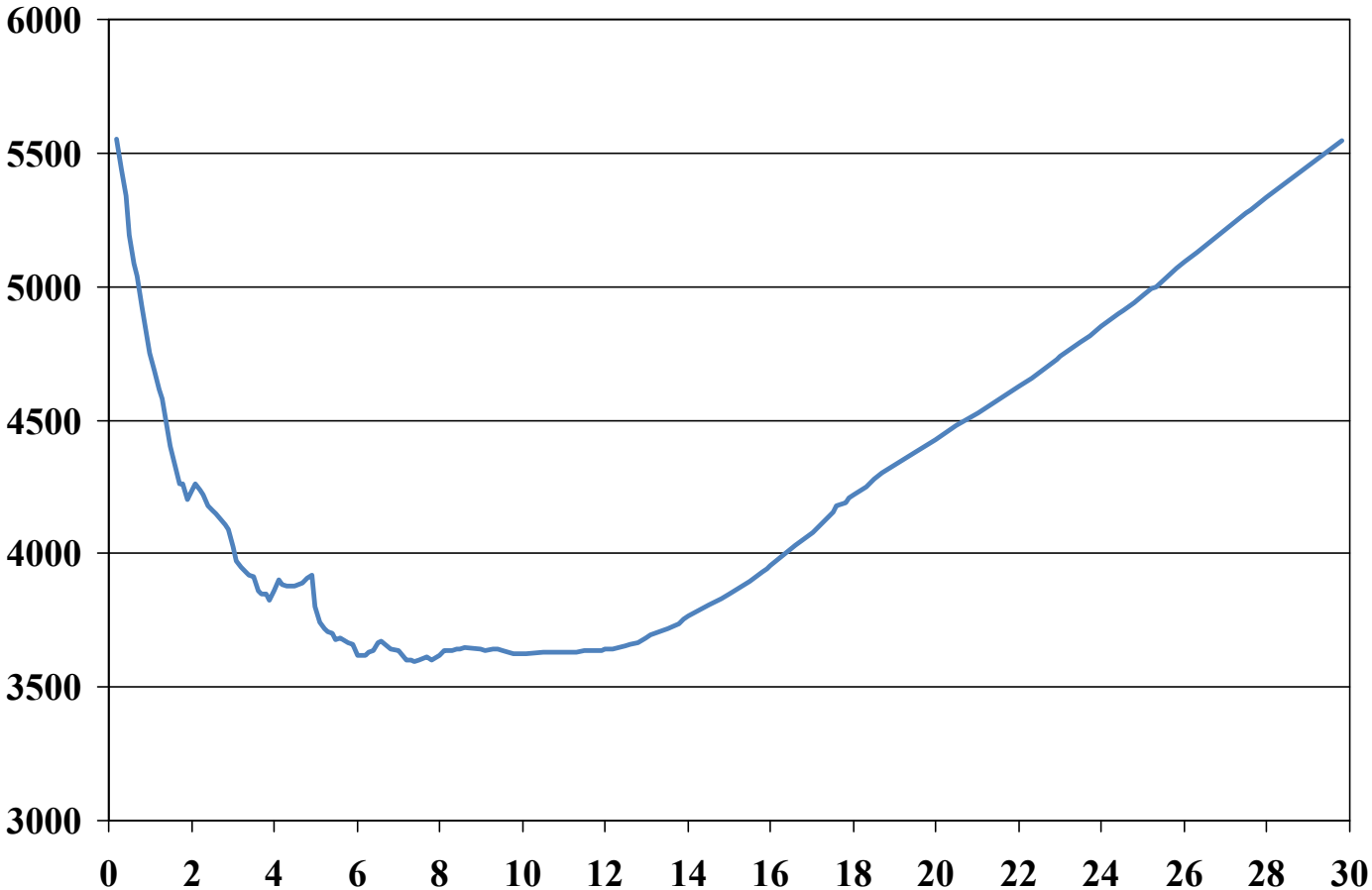
- Information on input quantities and prices by type of input and outputs by operation and individual plot (every three weeks).
- Multiple measures of plot quality and farmer ability.
- Market input price schedules (workers, machines, bullocks) by quantity of work time and by machine capacity.
- Information on how plots were acquired (inheritance date if inherited (almost all).
- Complete inventories of owned assets, values and quantities.
- Direct information on the capacities - productivity - of some individual farm machinery used in production.

The U Shape

- The data show that there is a U-shaped relationship between average profits (and output value) per acre.
- This is observed across plots within farmers and across farmers by total landholdings.
- Thus, we can dismiss the hypothesis that the patterns are due to credit constraints and farmer ability.
- There are other reasons that might make the observed patterns spurious: Measurement error in size that varies by size. Land quality.

Profits per Acre and Land Size

Figure 6. Relationship Between Real Average Profits per Acre and Farm Size (Acres) (ICRISAT VLS 2009-14)



Measurement and Land Heterogeneity Issues

- Is the relationship between average farm size and profitability per acre spurious?
- Possible that plot and farm size measured with error, and that the error is greater for larger plots (greater negative bias for larger scale and then smaller as scale increases at higher levels).
- Test using two independent measures of plot and land size, from the Census and the survey.

Two Sources of Land Data

- We use information reported in the 2009 round on dry and irrigated land that was inherited as an instrument for total land size reported in the 2009 survey round.
- 2009 reports of inherited land: Total acreage of dry and irrigated land inherited. 2009 reports are by individual plot size:
- Total land owned $= \sum$ plot sizes owned in 2009.
- We obtain estimates of land size on real profits by land size using the locally weighted functional coefficient model (LWFCM) of Cai, et al.(2006).

Measurement-error Corrected Estimates

- Are there deviations of the IV and OLS estimates?
- Do they differ by farm size?
- No evidence that measurement error or plot quality is systematically related to farm size.
- The U-shaped patterns we see are not spurious due to measurement error bias.

Measurement Error

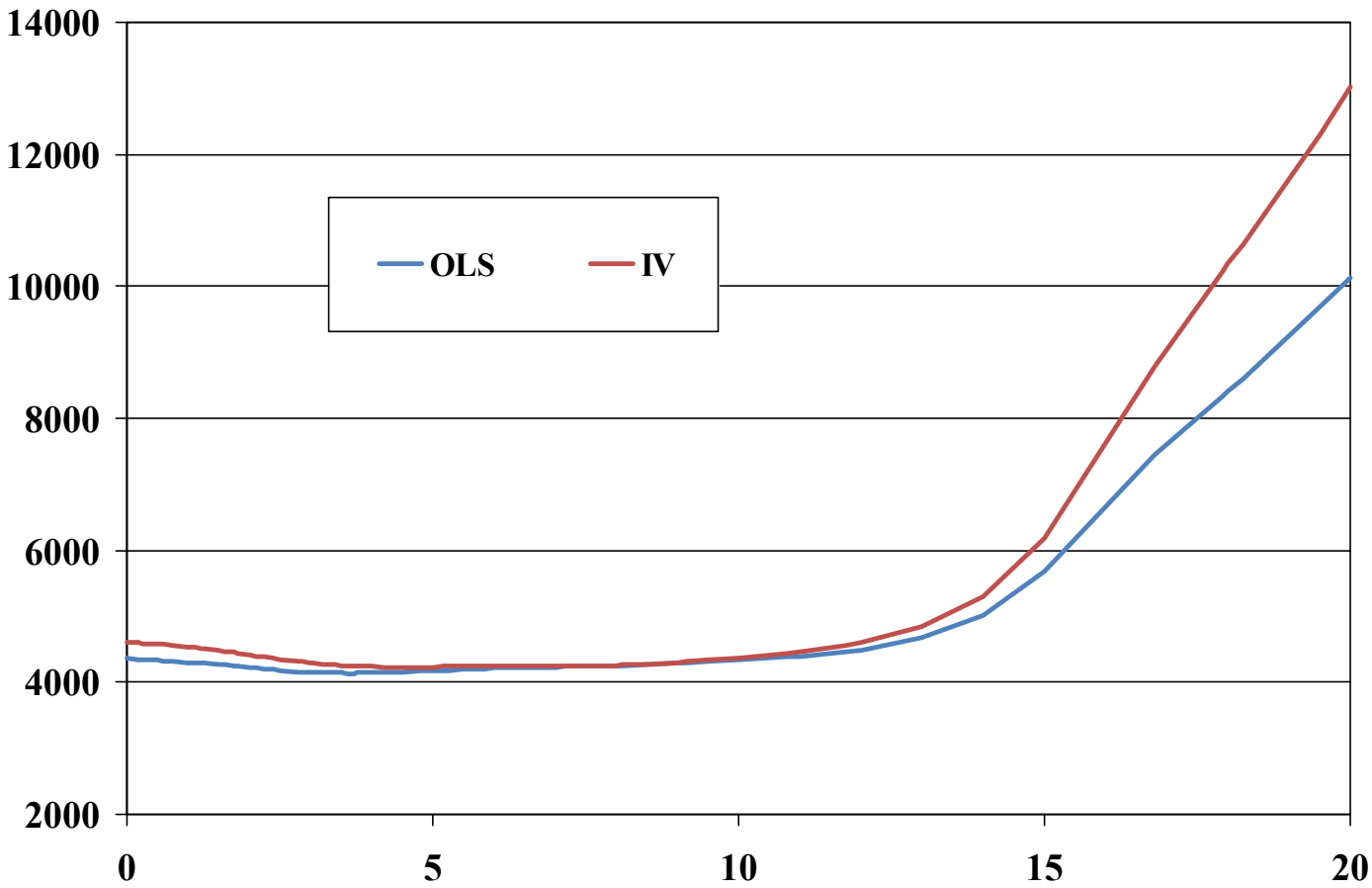
Table 1
Measurement Error Test: The Effect of Total Owned Area on Profits,
by Estimation Procedure, Using the Survey and Census Owned Land Self-reports in 2009

Variable	Profits		Owned Land - Survey
Estimation Procedure	OLS	IV	OLS
Total owned land - survey, sum of plot sizes	4324.2 (1305.8)	4433.5 (1328.1)	-
Owned land - Census, sum of irrigated and non-irrigated land	-	-	0.9637 (0.0128)
Village fixed effects	Y	Y	Y
N	306	306	306

Standard errors in parentheses clustered at the village level. Profits are for the *Kharif* season.

Measurement Error Effects

Figure 7. Measurement Error Effects: Profits and Owned Acreage Coefficient Point Estimates, by Farm Acreage and Estimation Procedure (ICRISAT VLS 2009)



Land Quality

What about land quality differences by size?
Have information at the plot level on:

- Soil depth (continuous)
- Soil fertility - 4 categories
- Soil degradation - 6 levels
- Soil type - 11 types
- Distance from the house (continuous) Location inside or outside the village

Land Quality

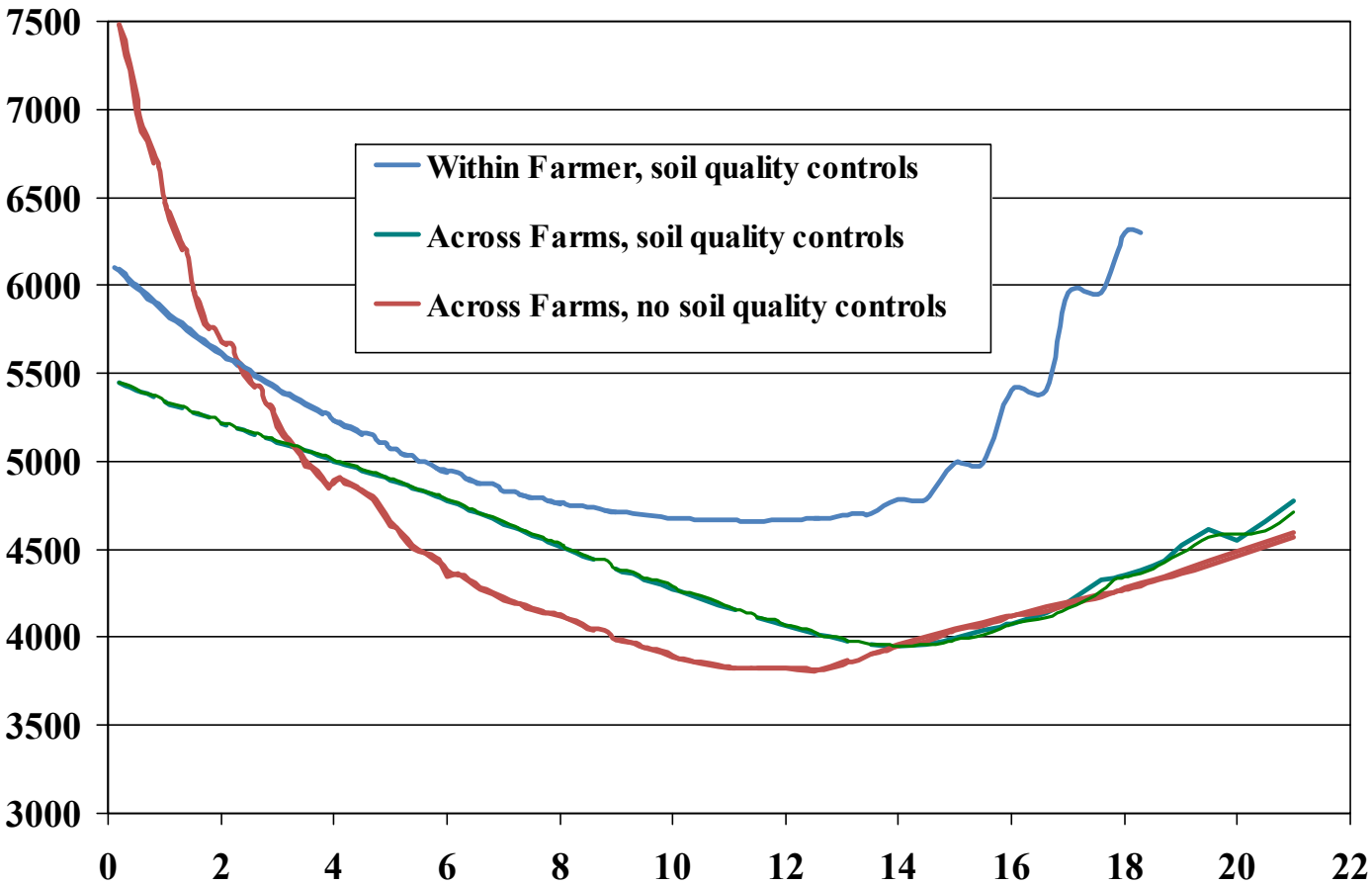
Table 2
Does Land Quality Affect Estimates of the Relationship Between Real Output Value and Profits and Area?
(*Kharif* Seasons 2009-14)

Variable	Real Output Value				Real Profits			
Farm size (acres)	9138.9 (676.3)	9053.4 (671.2)	-	-	3911.8 (501.4)	3871.9 (500.7)	-	-
Plot size (acres)	-	-	7390.6 (1463.8)	7548.6 (1506.0)	-	-	5841.8 (1474.0)	5939.5 (1521.7)
Village/year FE	Y	Y	-	-	N	Y	-	-
24 plot characteristics/categories	N	Y	N	Y	N	N	N	Y
Farmer/year fixed effects	N	N	Y	Y	N	N	Y	Y
H_0: Plot and household characteristics = 0 F(24,107) [p]	-	8.45 [.0000]	-	1.22 [.239]	-	3.61 [.0000]	-	1.22 [.245]
Number of observations	3,835	3,835	7,865	7,865	3,835	3,835	7,865	7,865

Standard errors in parentheses clustered at the village/year level.

Plot Quality and Farmer Fixed Effects

Figure 8. Real Profits per Acre by Owned Area: Roles of Plot Quality and Farmer Characteristics (ICRISAT VLS 2009-14)



Fixed Costs

Why might there be fixed costs?

- Labor demand is variable over the course of the crop year.
- Many tasks can be finished in a day or two.
- Labor typically hired on a daily basis
- Farms are spatially separated from residence
- Yale TN Survey
  - 23% from outside village
  - 63% of these by foot/bicycle avg 2km
  - 27% by bus avg 8km
  - 7 employers per worker in a season

Hourly Wage by Hours per Day

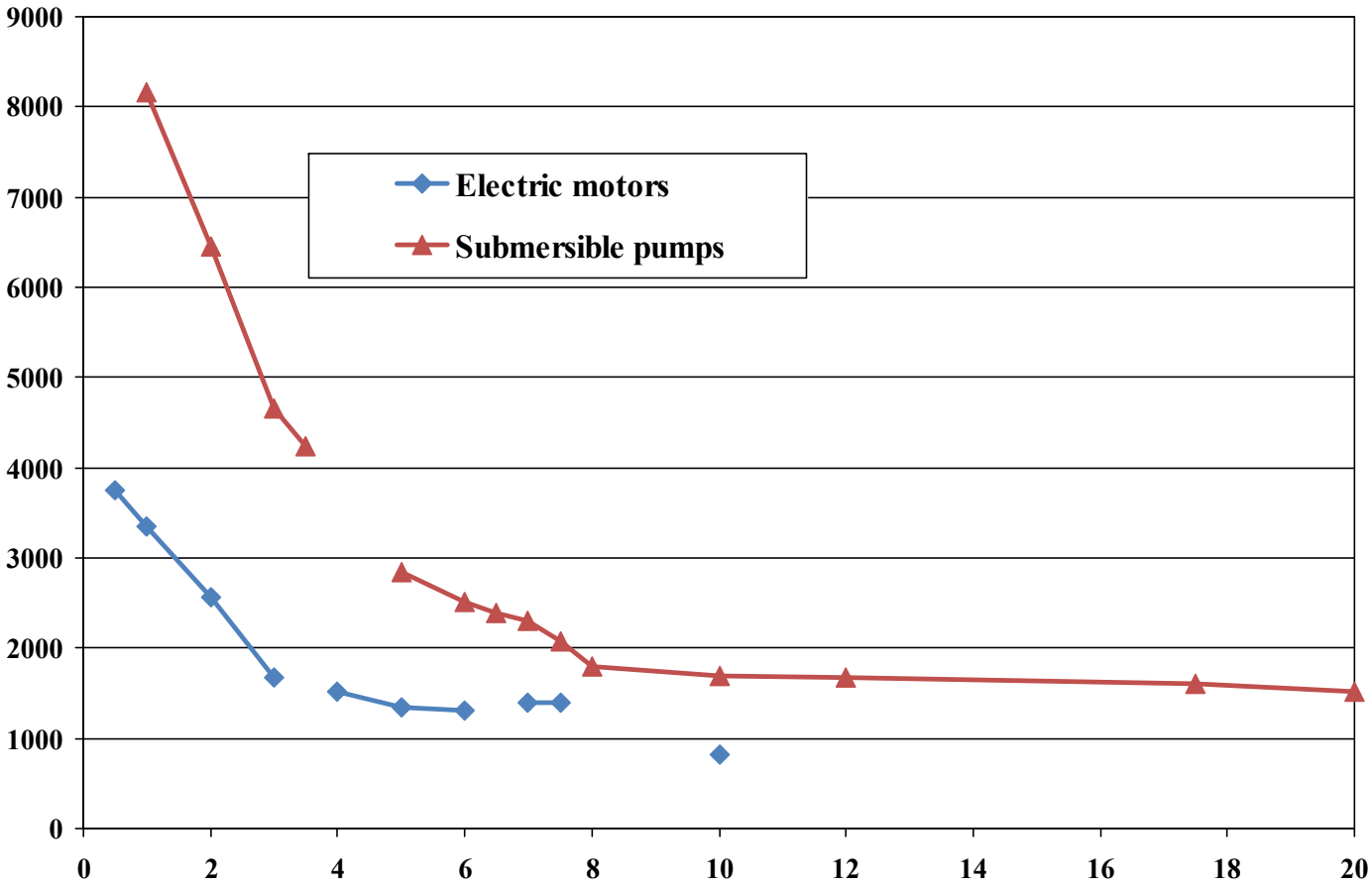
Table 3
Operation Fixed Effects Estimates:
the Percentage Difference in Hourly Wage Rates Paid for Eight Hours versus Less than Eight Hours of Work, by Input
(2010 and 2011 ICRISAT Monthly Price Schedules)

Variable	Hired Male Labor	Hired Bullock Pair + Driver
Worked eight hours in the day versus <8	-0.332 (0.0314)	-0.223 (0.0454)
Mean wage (rupees)	22.1 (9.34)	78.7 (39.6)
Percent working <8 hours	30.7	58.4
N	729	450

Standard errors in parentheses. Hourly wage rates constructed by dividing reported daily wages by the report of hours worked.

Cost per Horsepower

Figure 9. Cost per Horsepower for Electric Motors and Submersible Pumps by Horsepower (ICRISAT VLS Equipment Inventory, July 2011)



Key Features of Model

Can we explain the patterns we see?
U-shaped average and rising marginal returns Model that incorporates:

- Fixed, transaction costs of hiring labor.
- Travel, search (for labor), storage (for equipment).
- Results in falling average hourly wages with hours hired and thus with plot/farm size.
- Economies of scale in equipment - price and capacity
- Larger equipment more efficient than smaller units in terms of processed acreage per hour.

One-task model

To fix ideas we work with a one-task, one-period agricultural CRS production technology g in which the fundamental inputs are endowed land a and nutrition e. Total output is thus given by

$$g(a, e)$$

To begin, we assume that plant nutrition production is a function of labor only:

$$e = l_f + l_h$$

Compensation for search/transport cost

- Workers entering the labor market for off-farm work in the period face some fixed transaction cost f per period (search, travel).
- In equilibrium, employers wishing to employ workers even for just a few hours must partly compensate these workers for this fixed cost, so that the cost of hiring a worker for hours is $w(l_h) = (l_h > 0)\, w_0 + w_1 l_h$

Incidence

ICRISAT costs out family labor at the variable component of wages.
This is correct if

- the family is engaged in the external labor market regardless of on farm labor supply or
- the transaction cost f is fully compensated by the labor market.

Setup[

- We assume that the farmer has a fixed endowment of (family) labor l, and maximizes profits plus labor income minus any fixed costs of entry into the labor market.
- Profits are

$$\pi(a, l_h, l_f) = ag(l_h + l_f) - w(l_h) - w_1 l_f$$

- And the farmer maixmizes:

$$\pi(a, l_h, l_f) + (l_o > 0)(w_0 - f) + w_1 l_o$$

subject to

$$l_o + l_h = l$$

Regime 1

Given the transaction cost, there will be three regimes characterizing the use of family and hired labor with two land thresholds determined by the magnitude of f.
Regime 1 (a<a*)

- At the lowest levels of a farmers work both on farm and off farm and do not hire workers.
- The critical upper bound of landholdings a* for this regime at which the farmer is just indifferent between employing all family workers full time on the farm and some entering the labor market.

$$g(a^*, l) = g(a^*, {l_f}^*) + (w_0 - f) + w_1(l - {l_f}^*)$$

$$f_l(a^*, {l_f}^*) = w_1$$

Regime 2

Regime 2 (a*<a<a**)

- Because of the transaction costs, this is a non-trivial regime.
- Until that upper limit, from a*, as acreage increases, up to a**, average profitability declines, given the fixity of the family labor force.
- Labor per acre also declines with acreage.

Regime 3

Regime 3 (a>a**)

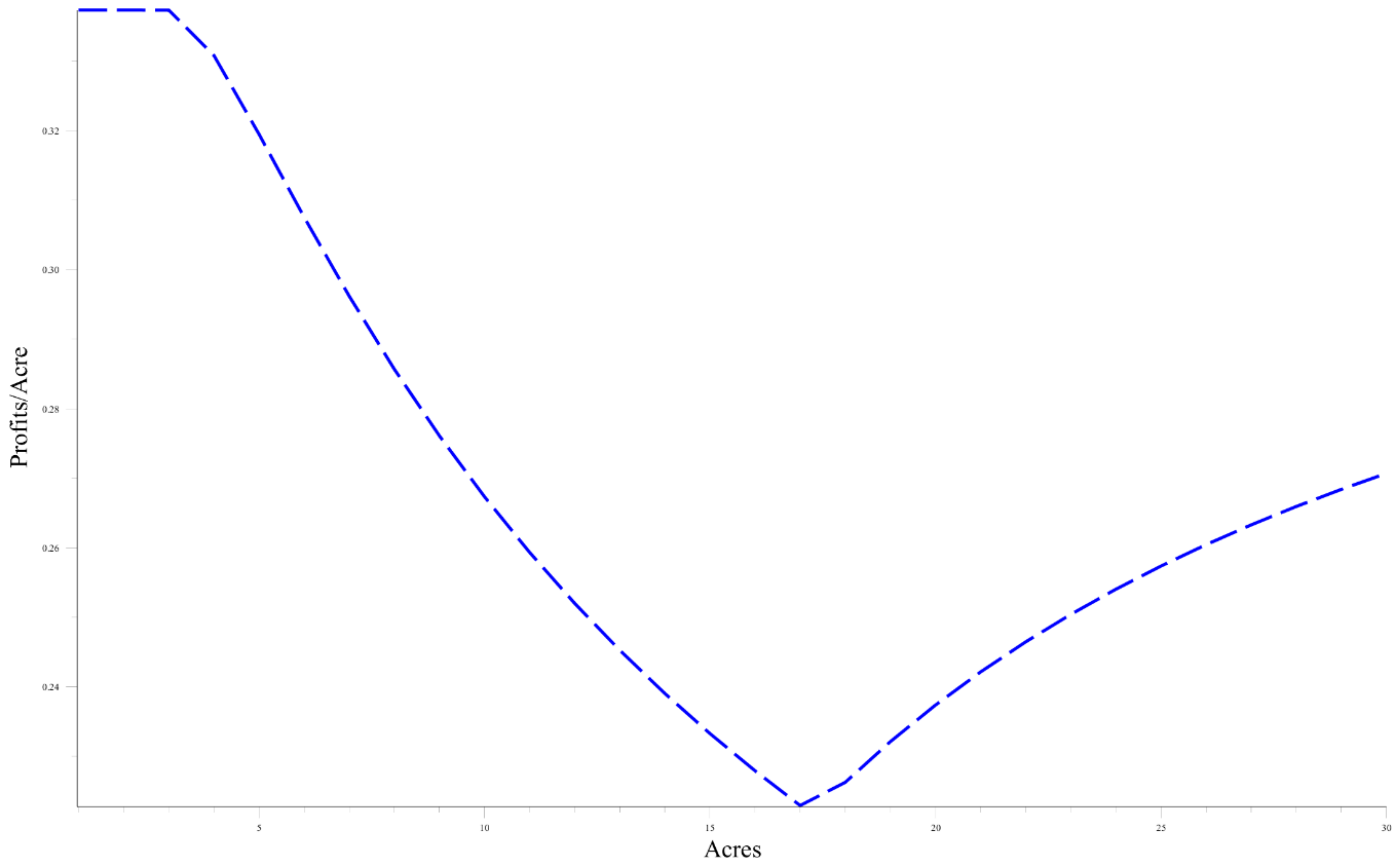
- Farmers hire workers
- Marginal cost of labor equals variable part of wage
- Average cost of labor falls as more workers are hired.
- Average profits rise.

$$f(a^{**}, l) = f(a^{**}, l + {l_h}^{**}) - w_0 - {w_1}^{**} l_h$$

$$f_l(a^{**}, l + {l_h}^{**}) = w_1$$

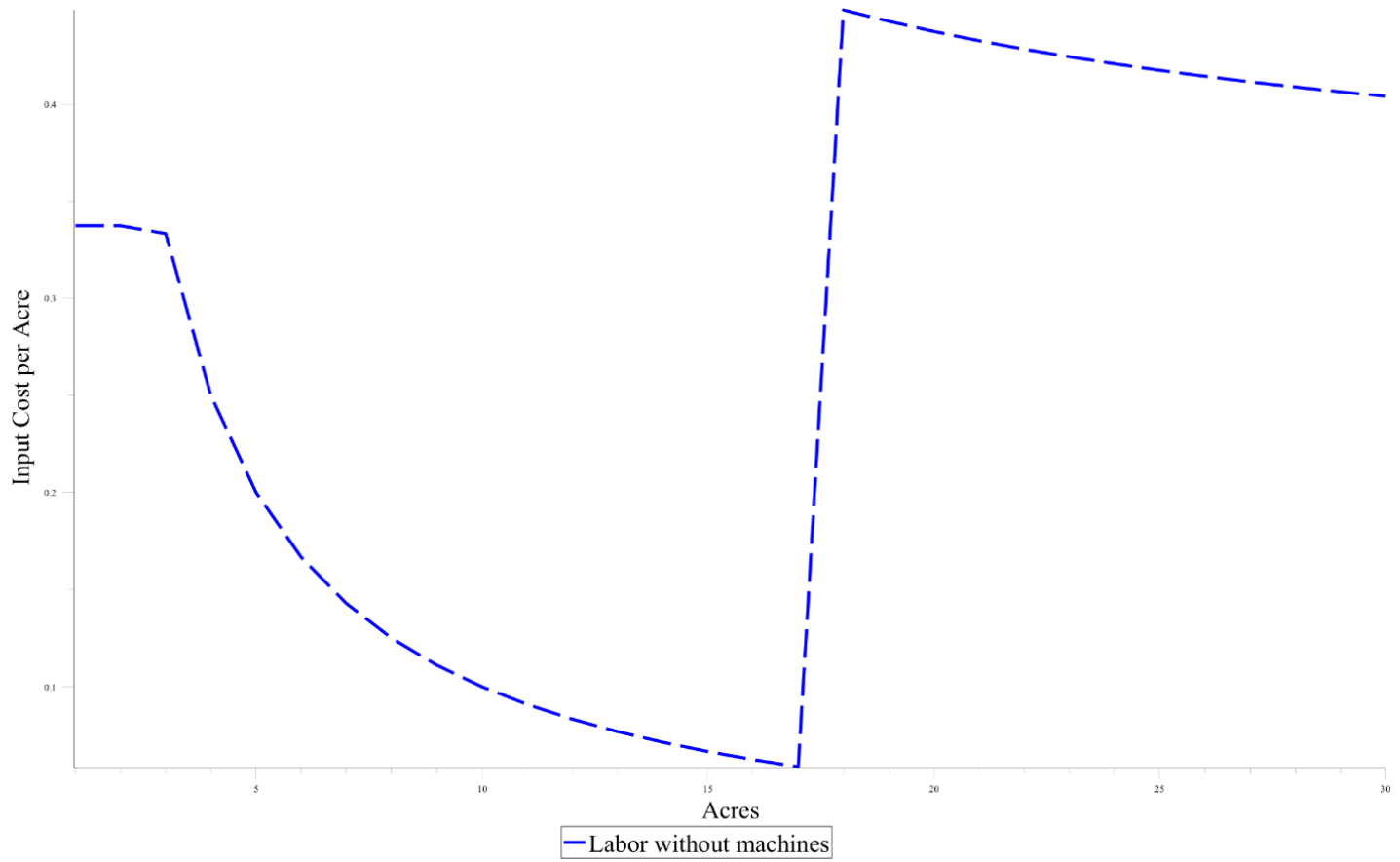
Profits per Acre: Labor Only

Figure 10: Profits per acre by farm-scale:
simulation based on the model with only labor



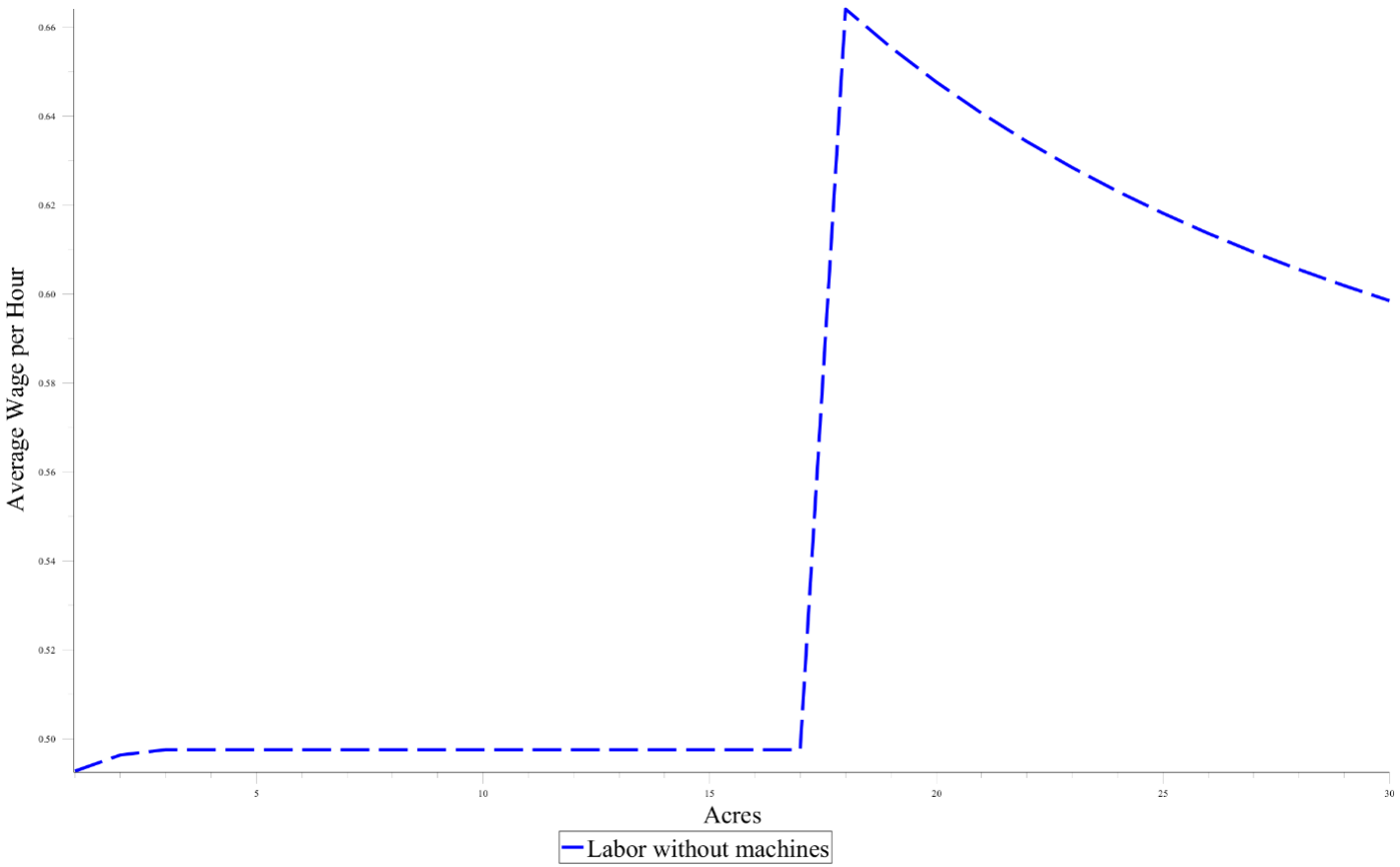
Input Costs per Acre: Labor Only

Figure 11: Input costs per acre by farm-scale:
simulation based on the model with only labor



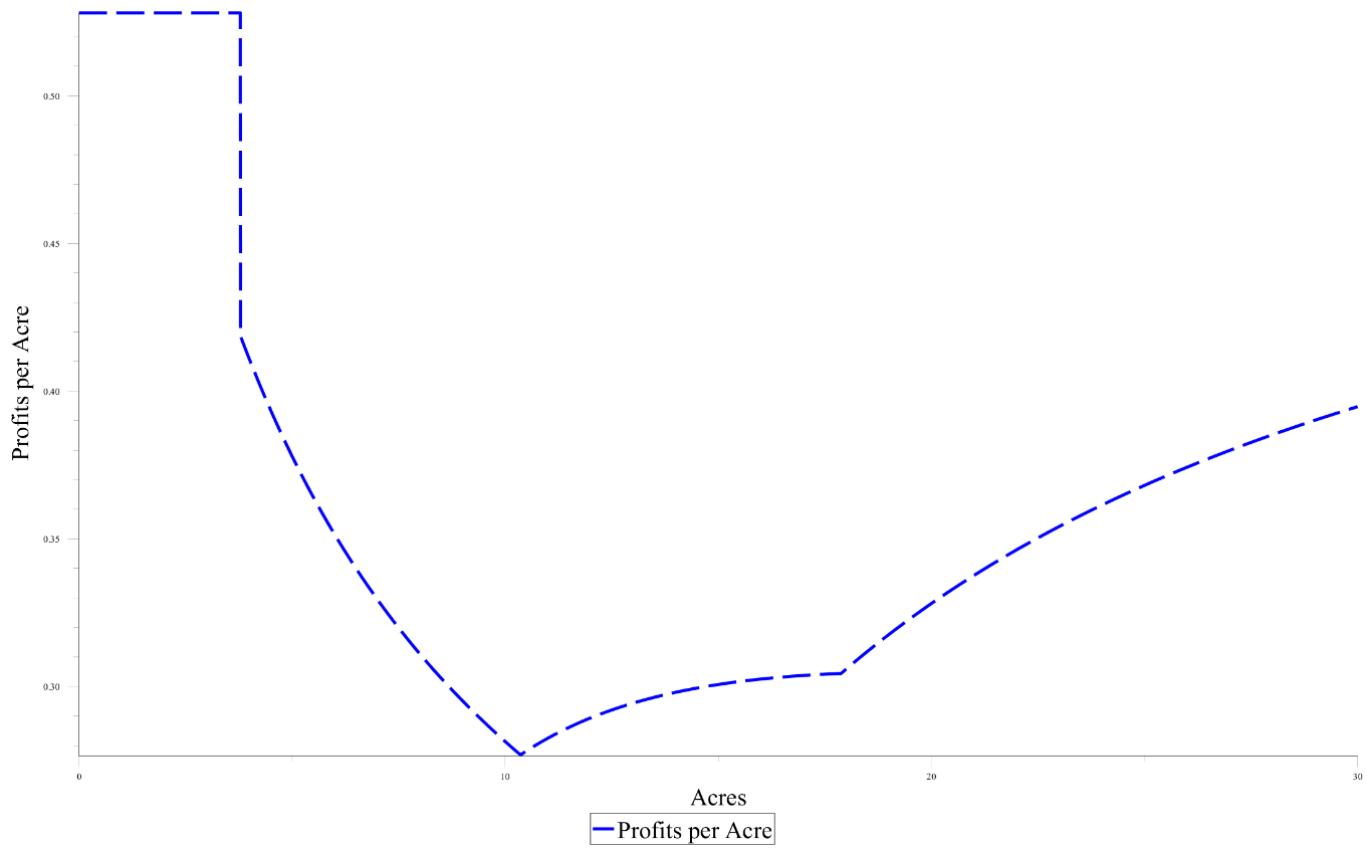
Wages: Labor Only

Figure 12: Average wage by farm-scale:
simulation based on the model with only labor



Profits per Acre: Two Stages

Figure 13: Profits per acre by farm-scale:
simulation based on the model with two labor stages



Heterogeneous Machinery

Adding Heterogeneous Machinery

- The labor-only model with fixed market costs can explain the U-shape for average profits.
- However, it is clearly inadequate for explaining how average profitability could ever be higher than that of the smallest farms.
- This is because average profitability reaches its maximum when the fixed cost component becomes an epsilon share of total labor costs. And that is always zero for the smallest farms.
- We now add the possibility of employing machinery, which can substitute for labor and is heterogeneous in capacity.

Modeling Capacity

- A key distinction for machinery: separate time and effective capacity q, the maximum amount of processed acreage per unit of time
- Effective capacity depends on both the machine and farm size: An 8-row harvester will not process any more acreage on a 4-row farm compared with a 4-row harvester.
- A power sprayer that can cover a radius of x yards would be no more effective than a weaker sprayer on farms where the radii of farmed area are significantly less than x.

Cost of Capacity

- Obviously, labor is heterogeneous too, but differences in manual agricultural labor within gender, at least within some stages, are sufficiently small as to not be reflected in time wages (Foster and Rosenzweig, 1993(!)).
- Farm machinery comes in different capacities, which are priced differentially.
- We assume that the cost of per unit of time of a machine of capacity q is

$$r_m = p_q q^{\nu}$$

Plant Protection Function

- The farmer chooses the capacity of the machine q and how much time m to employ it based on both acreage and price.
- To capture these ideas we redefine the nutrient production function as

$$e(I, q, m) = (\omega_I(\xi I)^\delta + \omega_m((1 - \frac{q}{\phi(a)})qm)^\delta)^{1/\delta}$$

Capacity Decision Separable

- Machine and labor hours are selected to maximize profits given optimal capacity.
- Note that a necessary condition for higher capacity machines to be used on larger farms is that $0<\nu<1$.
- Profit function

$$\pi(a, l_h, l_f, q, m) = g(a, e(l_h + l_f, q, m)) - w(l_h) - w l_f - (w\theta + p_q q^{\nu}) m$$

- Capacity solves

$$\frac{(\phi(a) - 2q)\theta w}{p} + (1-\nu) q^{\nu} \phi(a) - (2-\nu) q^{\nu+1}$$

Comparative Statics I

- Capacity is increasing in area if $\phi'(a) > 0$.

$$\frac{dq}{da} = \frac{q^2 \phi'(a)}{(\phi(a) - q)(\phi(a)\nu - 2q\nu - \phi(a) + 4q)}$$

- Capacity is increasing in wage (due to machine labor)

$$\frac{dq}{dw} = \frac{\theta q(\phi(a) - 2q)^2}{pq^{\nu}\nu\ (\phi(a) - q)(\phi(a)\nu - 2q\nu - \phi(a) + 4q)} > 0$$

Comparative Statics II

- Capacity is decreasing in machine price

$$\frac{dq}{dp} = -\frac{q(\phi(a) - 2q)^2 w\theta q^{-\nu}}{p^2\nu(\phi(a) - q)(\phi(a)\nu - 2q\nu - \phi(a) + 4q)} < 0$$

- Capacity is decreasing in elasticity of price wrt capacity

$$\frac{dq}{d\nu} = -\frac{q(\phi(a) - 2q)^2 w\theta q^{-\nu} \ln(q)}{\nu p(\phi(a) - q)(\phi(a)\nu - 2q\nu - \phi(a) + 4q)}$$

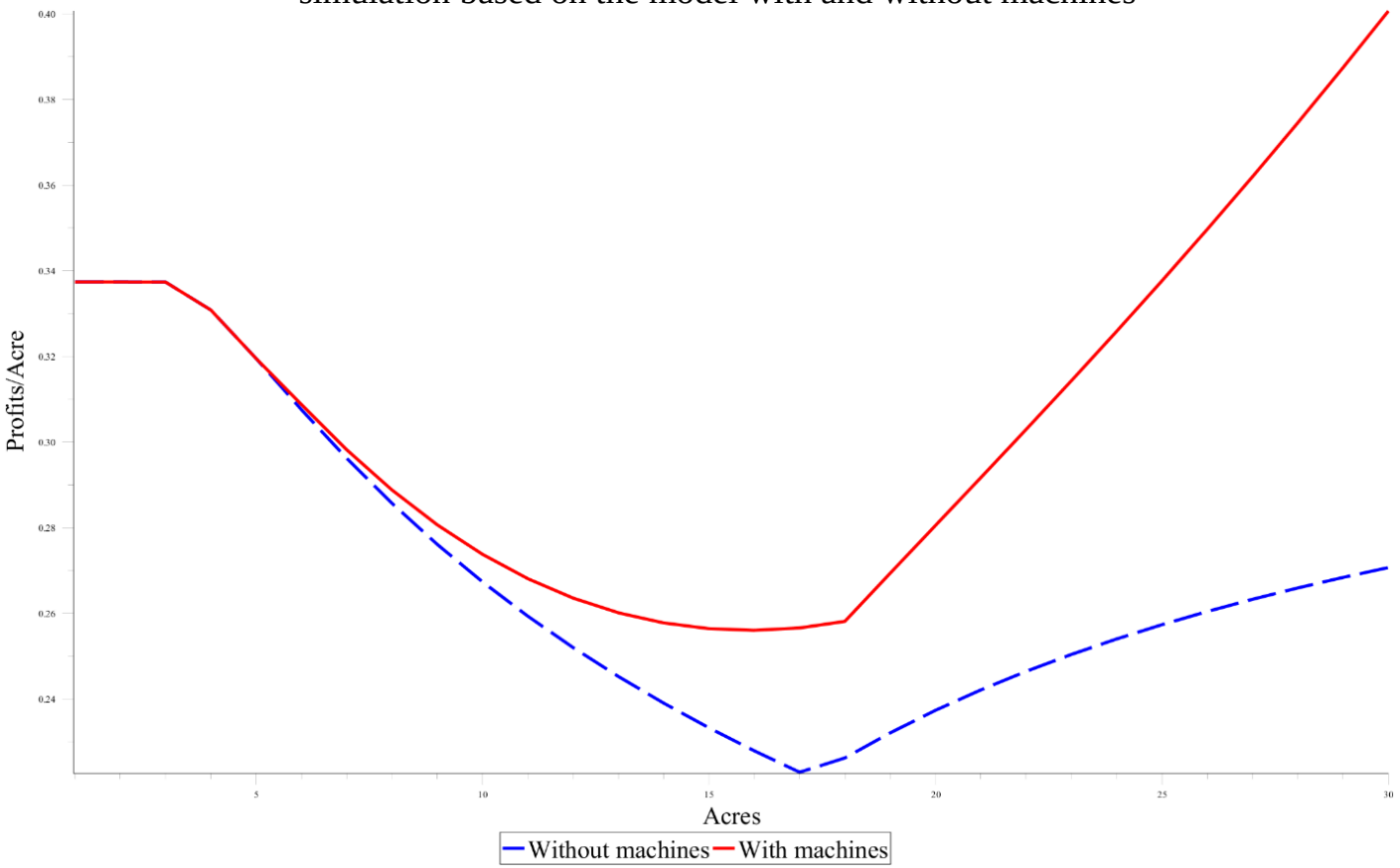
$$-\frac{q(\phi(a) - 2q)}{\nu(\phi(a)\nu - 2q\nu - \phi(a) + 4q)} < 0$$

Simulation with Machines

- We can also simulate this augmented model, computing average and marginal profitability by land size. In addition to the parameter values in the labor-only model, we set.
- Figure 14 displays average profits with and without the option for machine employment.
- The simulation with the machinery option also replicates the u-shaped relationship between farm (plot) size and average profits we see in the data.
- But now profitability is higher for large farms than for the smallest farms.

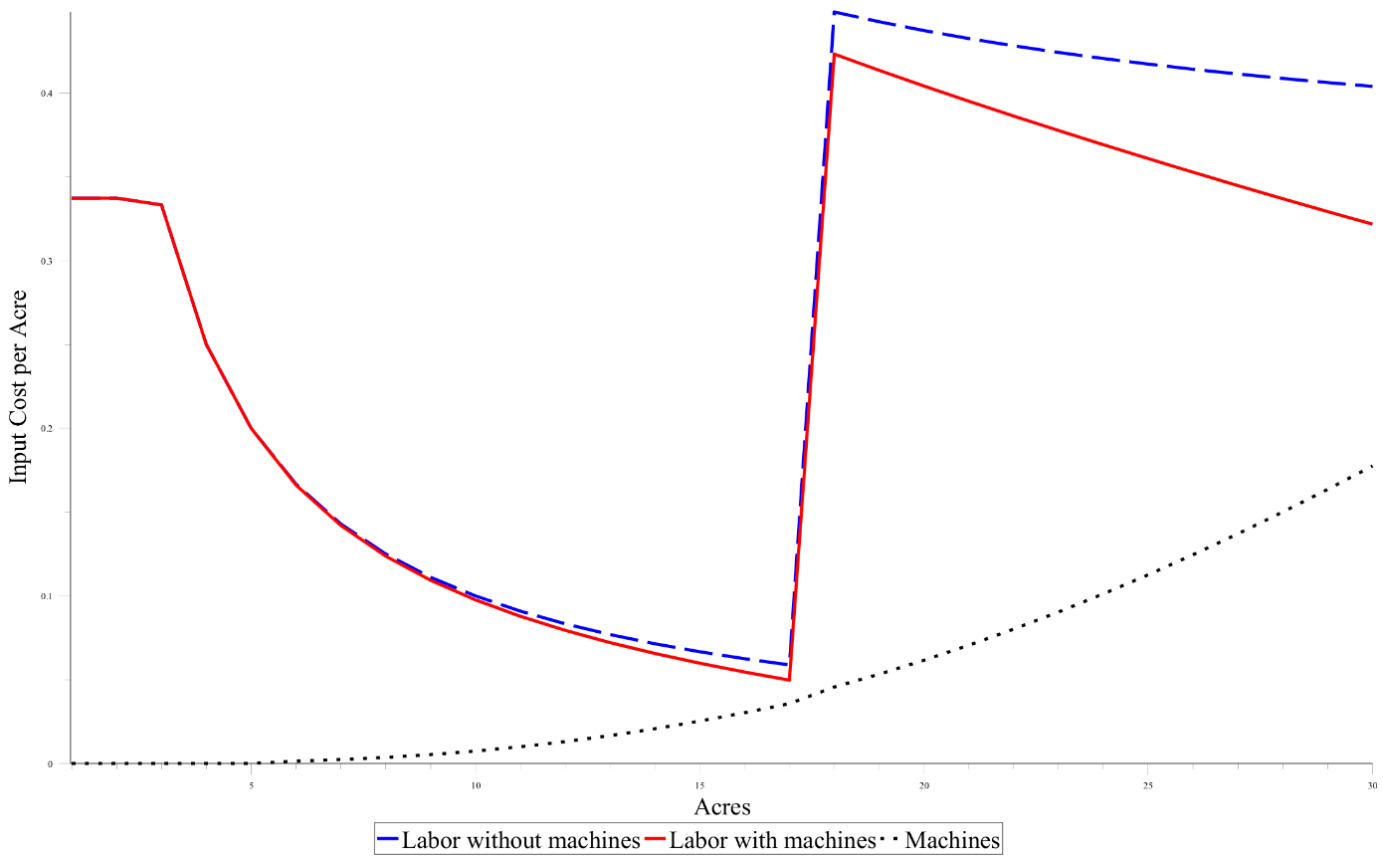
Profits per Acre: Machines

Figure 14: Profits per acre versus farm-scale:
simulation based on the model with and without machines

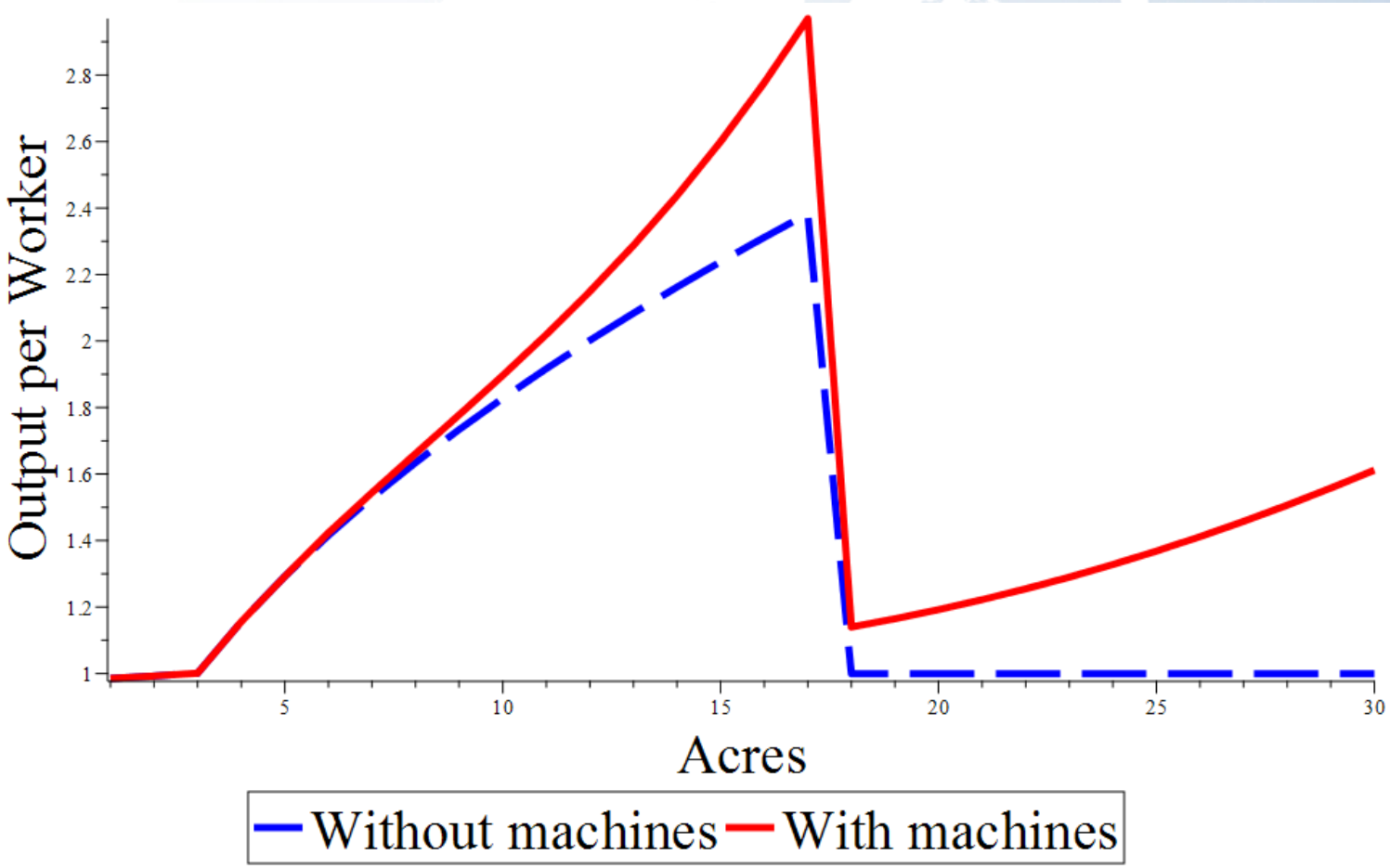


Cost per Acre: Machines

Figure 15: Labor and machine costs per acre versus farm-scale: simulation based on the model with and without machines



Output per Worker



Estimating Production Function

- Consider labor only model

$$y = a^{\alpha} {l_e}^{1-\alpha}$$

- Estimate in logs

$$\ln y = \beta_0 + \beta_1 \ln a + \beta_2 \ln l_e$$

- Scale economies are not evident regardless of regime

$$\frac{\partial \ln y}{\partial \ln a} = \beta_1 = 1 - \beta_2 = 1 - \frac{\partial \ln y}{\partial \ln l_e} = \alpha$$

Profit Function

- Regime 1 profit function

$$\pi = a^{\alpha} l_f^{1-\alpha} - w_1 l_f$$

- Estimated in logs

$$\ln \pi = \beta_0 + \beta_1 \ln a$$

- Regime 1: Constant returns

$$\beta_1 = 1$$

- Regime 2: Decreasing returns

$$\beta_1 = 1/(1 + \frac{(1-\alpha)(a/l)^{\alpha} - w_1}{\alpha(a/l)^{\alpha}}) < 1$$

- Regime 3: Increasing returns

$$\beta_1 = 1/(1 - \frac{w_0}{\alpha a^{\alpha} l_e^{1-\alpha}}) > 1$$

With Machines

- Profit function optimized with respect to q for $\theta = 0$

$$\pi = a^{\alpha}(m\phi(a)\frac{1-\nu}{(2-\nu)^2})^{1-\alpha} - (p(\phi(a)\frac{1-\nu}{2-\nu})^{\nu})m$$

- Again estimate

$$\ln \pi = \beta_0 + \beta_1 \ln a$$

- Identify increasing returns if $\phi'(a) > 0$

$$\beta_1 = 1 + \frac{aq\,(1-\alpha)\,\phi'(a)}{\alpha\,\phi(a)\,(\phi(a)-q)}.$$

Summary

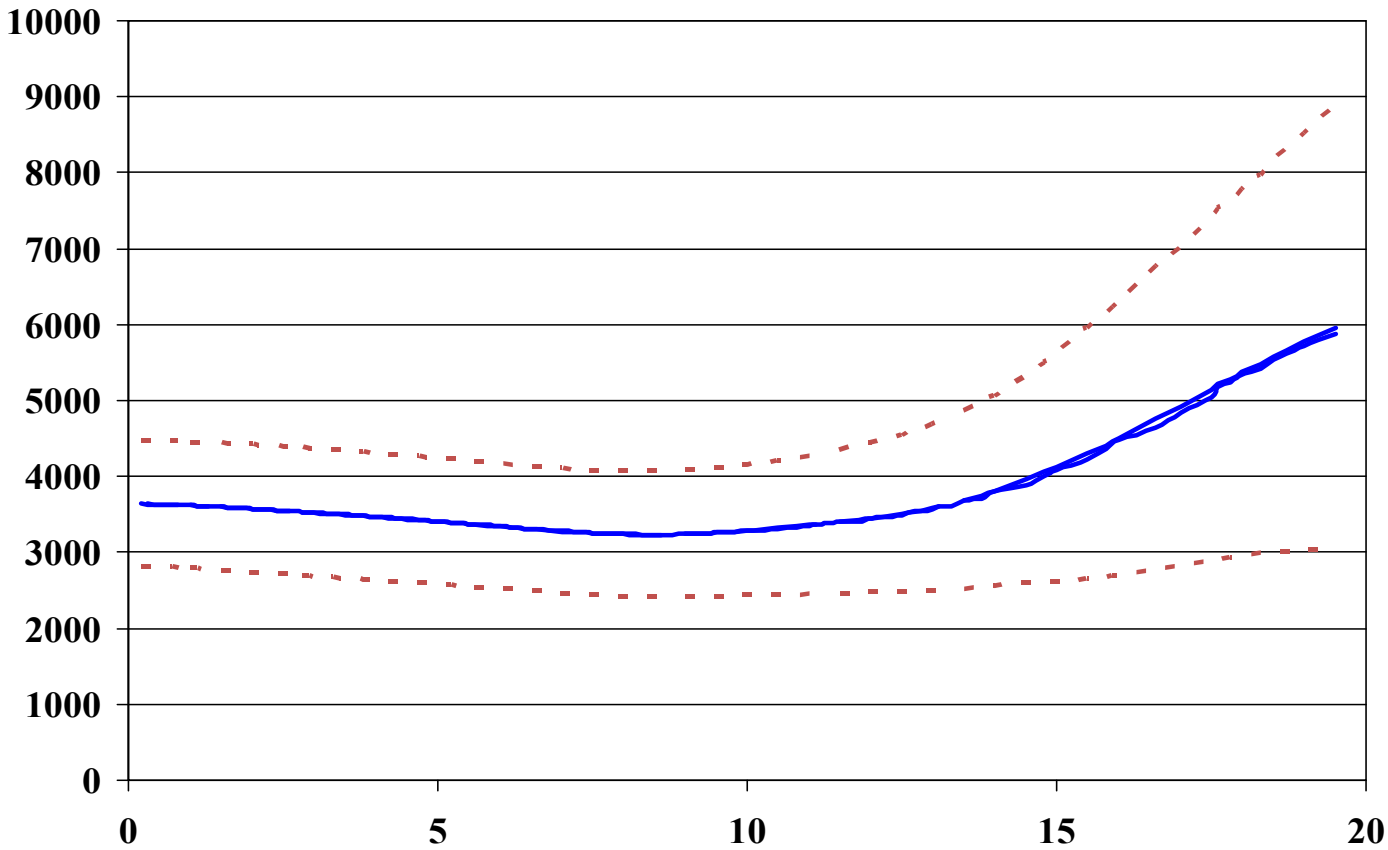
- Thus, estimating the production function will correctly identify that there are not scale economies in the production functions.
- However, such an approach will miss the presence of scale economies more generally.
- The reason is that the fixed costs of labor affect the cost of inputs and thus the level of inputs but not the relationship between inputs and outputs.
- We also similarly show that estimating the production function does not identify the source of scale economies when these are due to scale economies in machine capacity.

Key Findings

- Profits fall then rise with Land Size.
- Off-farm work falls with Land Size
- Labor costs fall with farm size
- Fraction of low hours and average hired wage declines with plot size
- Rainfall increases hours and *decreases* average hired wage

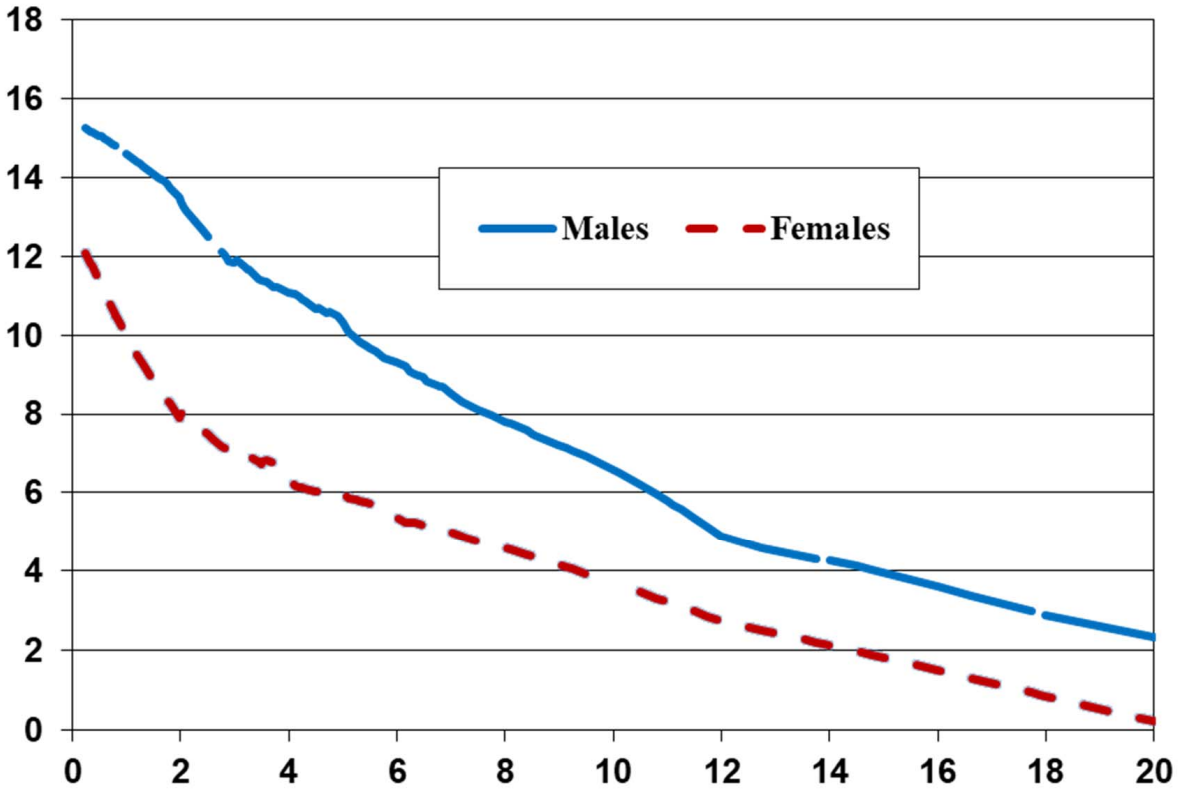
Predicted Profits by Land Size

Figure 16. LWFCM Estimates of the Effects of Land Size on Profits with 95% CI, Net of Soil Quality and Time/Village Fixed Effects, by Farm Size (ICRISAT VLS, 2009-14)



Off Farm Work by Farm Size

Figure 17. Average Days per Month Worked Off Farm, by Farm Size
Male and Female Workers Aged 21-59
(ICRISAT VLS 2014)



Labor Costs per Acre

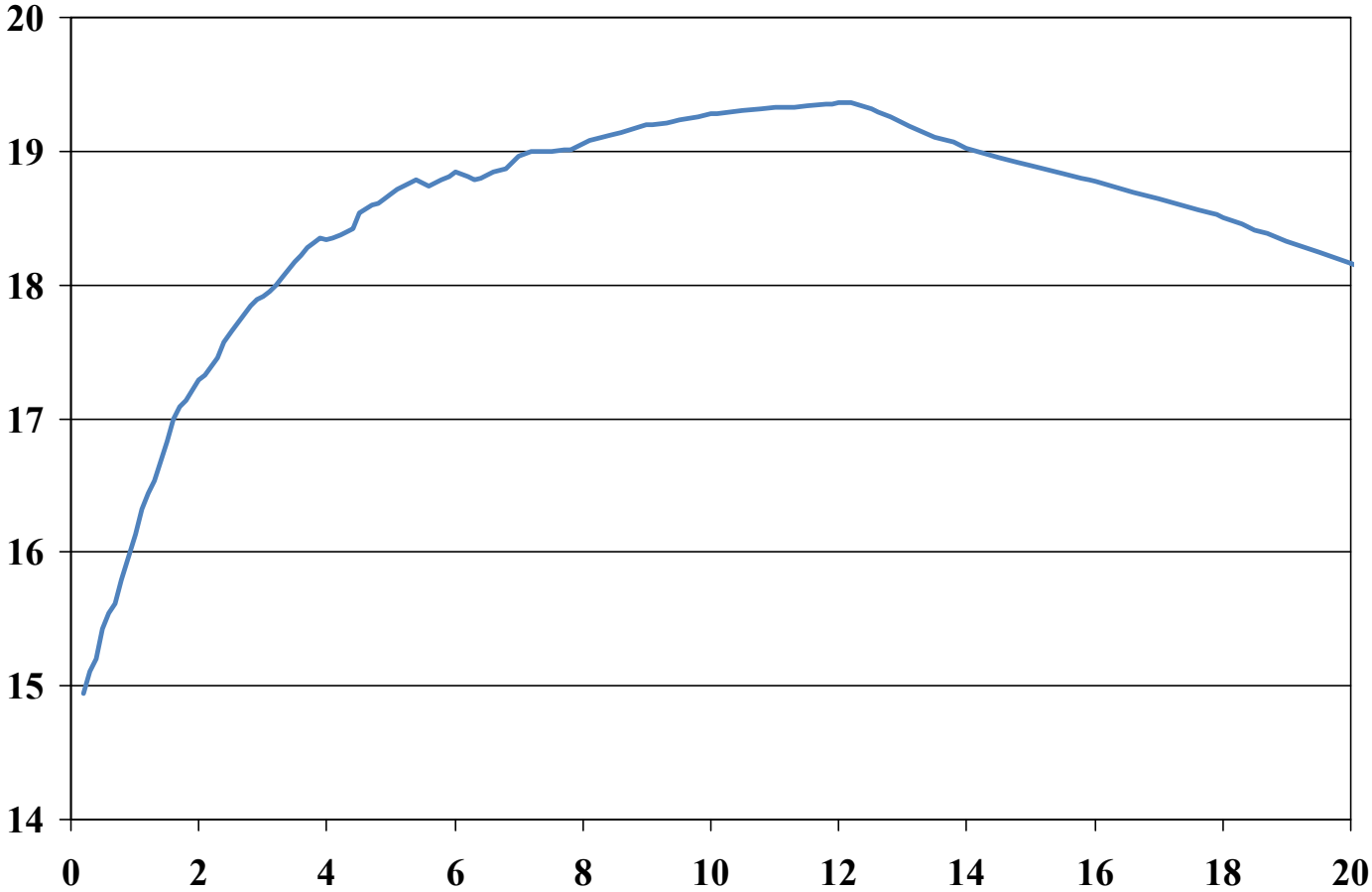
Table 4
Log Total Labor Costs per Acre and Area: Cross-Farm and Within-Farm Estimates
(*Kharif* Seasons 2009-14)

Variable	(1)	(2)	(3)	(4)
Farm size (acres)	-0.0576 (0.00750)	-0.0388 (0.00486)	-	-
Plot size (acres)	-	-	-0.0497 (0.0172)	-0.0437 (0.0168)
Village/year FE	Y	Y	-	-
24 plot characteristics/categories	N	Y	N	Y
Farmer/year fixed effects	N	N	Y	Y
H_0: Plot and household characteristics = 0 F(24,107) [p]	-	3.99 [.0000]	-	8.17 [.0000]
Number of observations	3,177	3,177	5,786	5.786

Standard errors in parentheses clustered at the village/year level.

Average Wage by Farm Size

Figure 18. Average Hourly Wage Paid for Male Labor, by Farm Size (ICRISAT VLS 2009-14)



Low Hours Usage

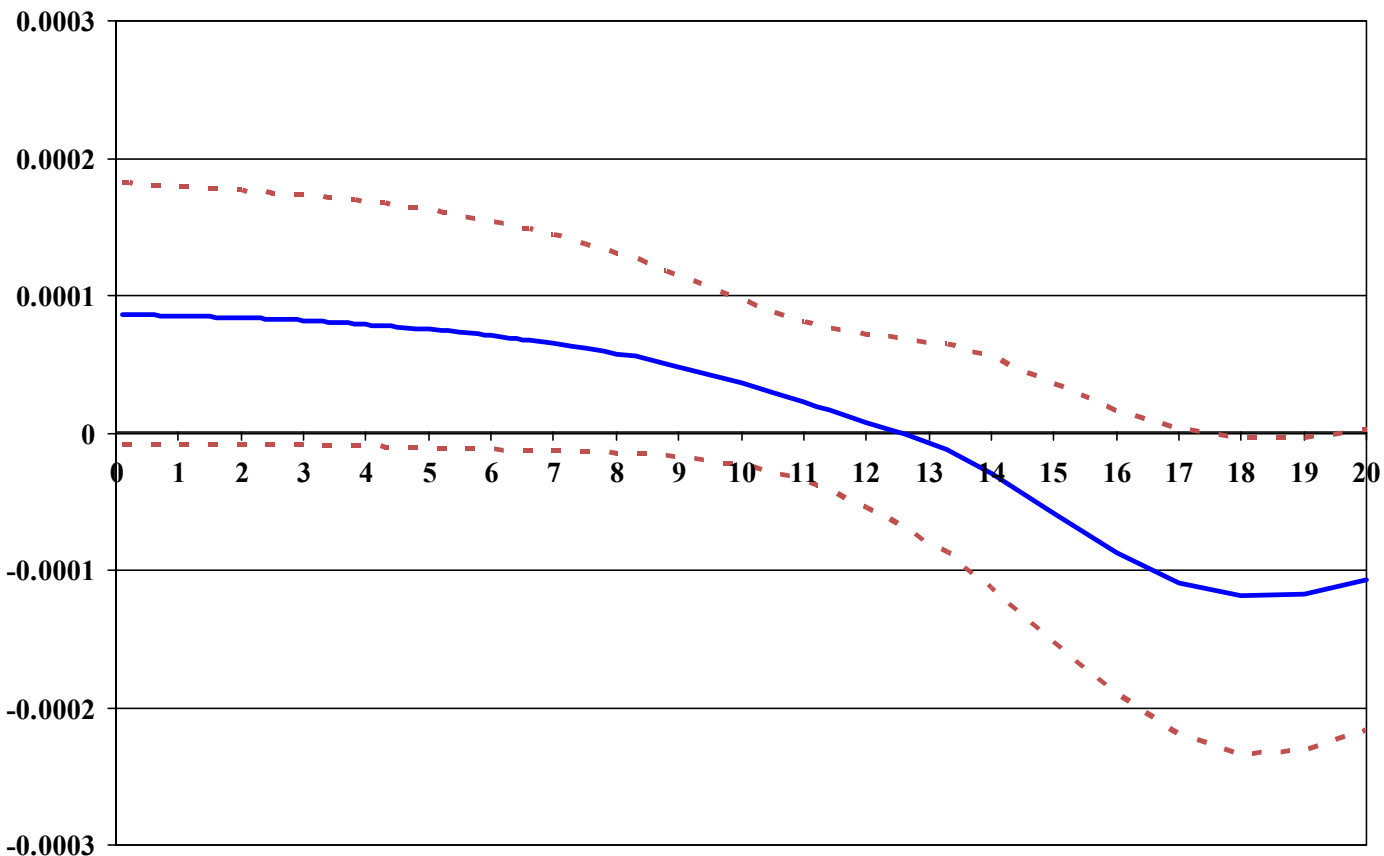
Table 5
Plot Size and Fraction of Operations that Employ Hired Inputs at Low (<=6) Daily Hours and the Average Hourly Wage Paid, by Input Type (*Kharif* Seasons 2009-14)

Variable	Fraction of Operations <6 Hours/Day			Average Hourly Wage		
Input type	Hired Male Labor	Hired Tractor	Hired Bullock Pair	Hired Male Labor	Hired Tractor	Hired Bullock Pair
Plot size (acres)	-.0165 (.00306)	-.0197 (.00247)	-.0170 (.00306)	-.183 (.0876)	1.25 (.769)	-.866 (.306)
Plot size squared x10^{-3}	.450 (.112)	.449 (.0682)	.555 (.117)	8.29 (3.23)	18.3 (32.4)	29.3 (10.9)
Village/year FE	Y	Y	Y	Y	Y	Y
25 Plot and household characteristics	Y	Y	Y	Y	Y	Y
Number of observations	6,777	6,777	6,777	6,777	6,777	6,777

Standard errors in parentheses clustered at the village/year level.

Effect of Rainfall on Low-Hours

**Figure 19. LWFCM Plot Fixed Effect Estimates:
The Effect of Rainfall on the Fraction of Operations Using Low-Hours Hired Male Labor,
with 95% CI, by Plot Size (ICRISAT VLS 2009-14)**



Rainfall Effects on Labor

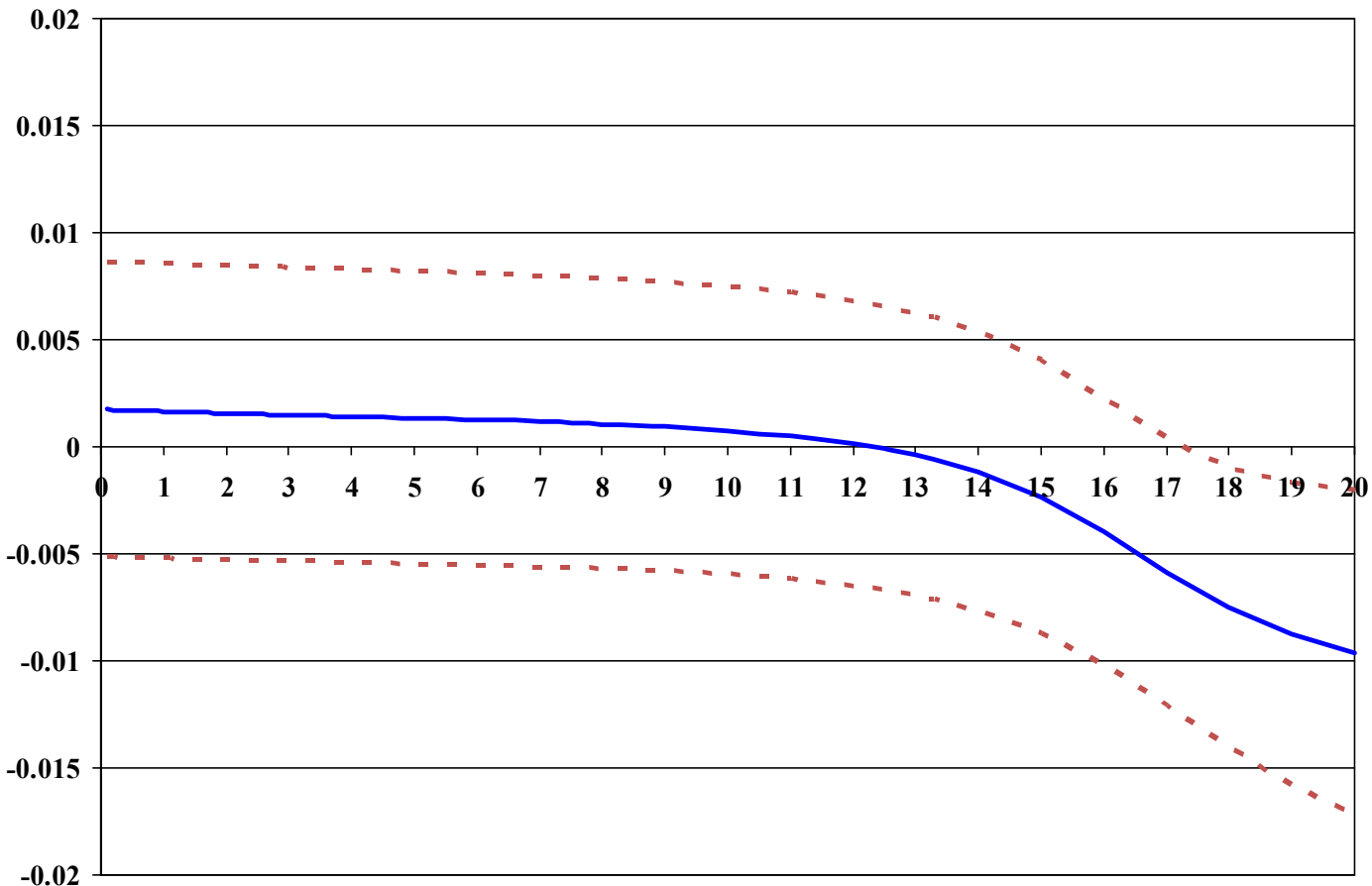
Table 6
Plot Fixed Effects Estimates: The Effects of *Kharif*-Season Rainfall on Profits, Hours Employed and Average Hourly Wage Rates, by Input Type (*Kharif* Seasons, 2009-14)

Variable	Profits	Hours Employed			Average Hourly Wage		
Input type	-	Hired Male Labor	Hired Tractor	Hired Bullock Pair	Hired Male Labor	Hired Tractor	Hired Bullock Pair
Rainfall (mm)	38.1	.182	.00362	.0347	-.0158	.0130	-.0593
	(17.1)	(.0701)	(.00316)	(.0248)	(.00672)	(.0601)	(.0355)
Rainfall squared x10^{-3}	-21.2	-.107	-.00214	-.0500	.00778	-.0132	.0757
	(8.59)	(.0377)	(.00161)	(.0268)	(.00398)	(.0282)	(.0331)
Year and plot FE	Y	Y	Y	Y	Y	Y	Y
H_0: Rain and rain squared = 0 F(2,n) [p]	3.09	4.18	0.99	1.97	3.47	0.28	3.02
	[.0504]	[.0183]	[.3742]	[.1452]	[.0352]	[.7589]	[.0538]
Number of observations	5,291	3,987	4,016	2,523	3,987	4,016	2,523

Standard errors in parentheses clustered at the village/year level.

Effect of Rainfall on Wage

**Figure 20. LWFCM Plot Fixed-Effect Estimates:
the Effect of Rainfall on the Average Male Wage, with 95% CI, by Plot Size
(ICRISAT 2009-14)**



Results for Machines

- Land Size increases mechanization net or wealth
- Capacity increases more than propotionately with cost
- Sprayer time decreasing in area
- Per hour sprayer price increases with Land Size
- Sprayer flow-rate increases with Land Size

Wealth and Mechanization

Table 7
Farm Size, Wealth and Mechanization (Ownership): 2014 ICRISAT VLS Round

Variable	Owns a Tractor	Owns a Power Sprayer	
Sample	All Farmers	All Farmers	Farmers Who Own Any Sprayer
Total owned land (acres)	.0125 (.00415)	.0107 (.00474)	.0133 (.00494)
Total rental value of land (wealth) x 10^{-5}	.0506 (.0146)	.0512 (.0166)	.0273 (.0144)
Village FE	Y	Y	Y
Percent owning	3.5	10.3	24.8
Number of farmers	652	652	288

Standard errors in parentheses clustered at the village level. All specifications include the head's age and schooling.

Fraction using Machines

Figure 21. Fraction of Farms using Sprayers and Tractors, by Farm Size (ICRISAT VLS 2009-14)



Sprayer Costs

Table 8
Cost and Capacities of Indian KrisanKraft Power Sprayers, 2017

Power sprayer	Litres/Hour	Current Price (Rupees)
	180	7830
	420	12260
	1320	25900
	2400	27900

Sprayer Time and Weeding

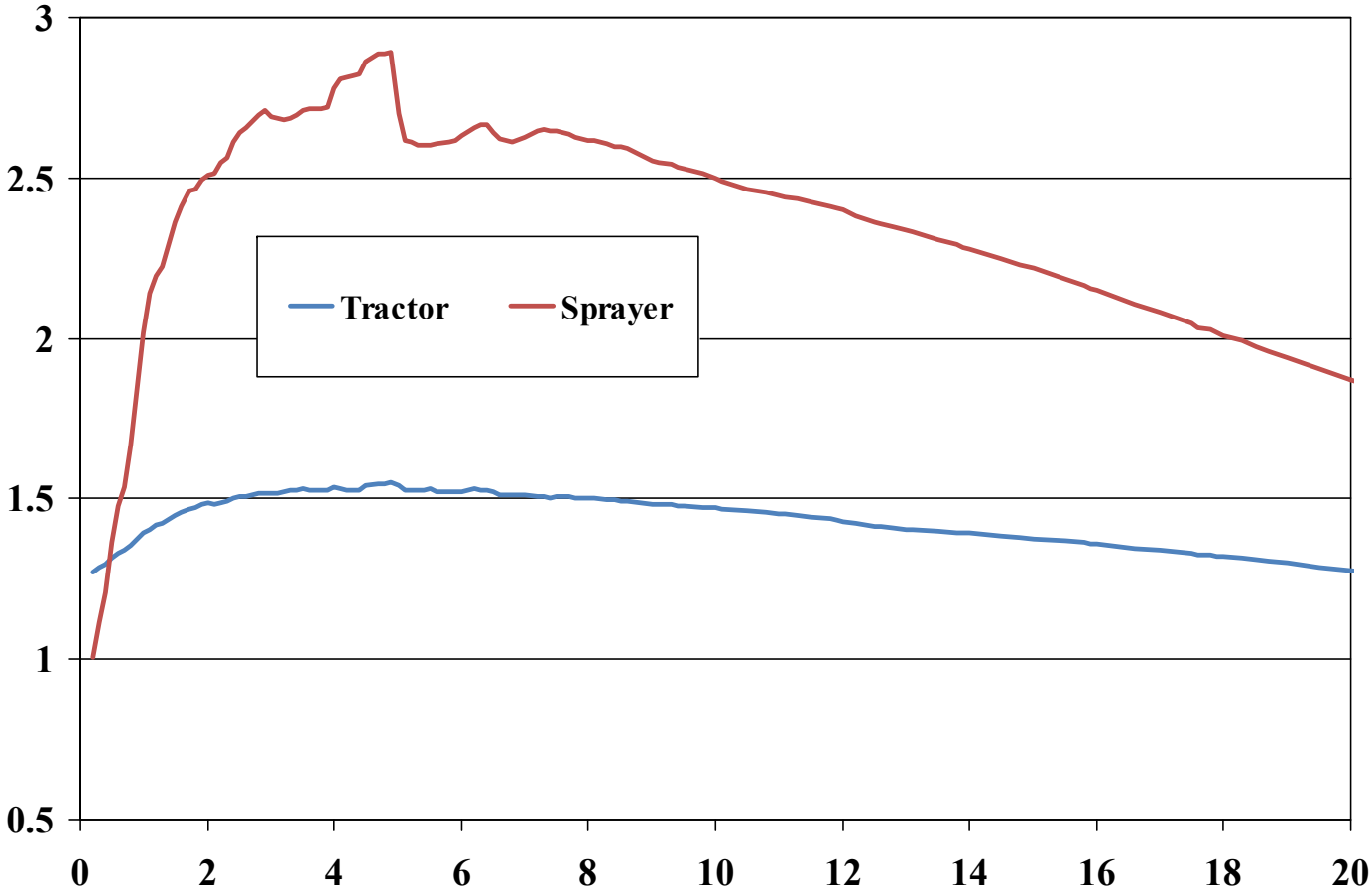
Table 9
Estimates of the Effects of Owned Land Size
on Sprayer Use, Weeding Hours per Acre, Sprayer Hours per Acre, Log Sprayer Price per hour, and Sprayer Flow Rate

Variable	Any sprayer use	Weeding hours per acre	Sprayer hours per acre	Sprayer log price per hour	Sprayer flow rate
Estimation procedure	OLS	OLS	OLS	OLS	OLS
Owned area	0.006197 (0.0009879)	-0.5631 (0.1286)	-0.4063 (0.0853)	0.01335 (0.00669)	0.01360 (0.00667)
All land characteristics	Y	Y	Y	Y	Y
Village/year fixed effects	Y	Y	Y	Y	Y
N	3,374	3,374	1,219	1,219	1,219

Standard errors in parentheses clustered at the village/year level.

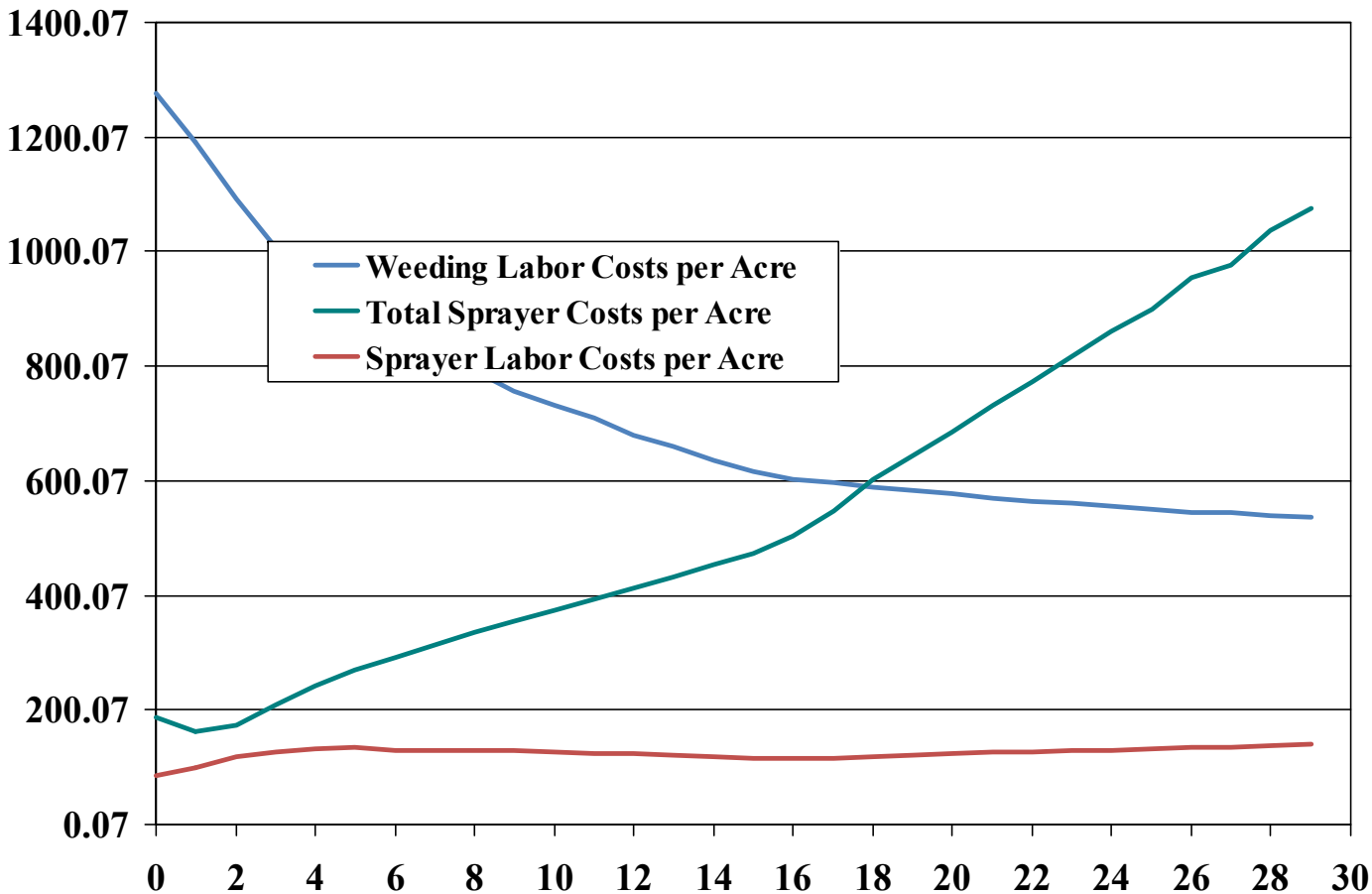
Equipment Hours

Figure 22. Per-Acre Equipment Hours for Tractors and Sprayers, by Farm Size (ICRISAT VLS 2009-14)



Weeding and Spray Costs

Figure 23. Real Weeding and Sprayer Labor Costs and Total Sprayer Costs per Acre, by Farm Size (ICRISAT VLS 2009-14)



GMM

Normalize and subtract capacity equation to remove village-specific effects

- Capacity first order condition

$$Q_{ij} = \frac{(1-\nu)\, {q_{ij}}^{\nu} \phi\left(a_{ij}\right) - (2-\nu) {q_{ij}}^{\nu+1}}{\left(\phi\left(a_{ij}\right) - 2\, q_{ij}\right)}$$

$$E(Q_{ij} - Q_{i'j} | a_{ij}, a_{i'j}) = 0$$

- Sprayer cost

$$E\left(\ln(x_{ij}) - \nu \ln(q_{ij}) - \ln(x_{i'j}) - \nu \ln(q_{i'j}) \middle| a_{ij}, a_{i'j}\right) = 0$$

Sprayer Time and Weeding

Table 10
GMM Estimates of the Effective Capacity Function $\varphi(a)$ and Price Parameter υ

Coefficient	Point Estimate	Robust SE
υ	0.316	0.124
b_0	5.58	0.0375
b_1	0.933	0.0343
b_2	-0.0190	0.00211
H_0: $\upsilon < 1$, $\chi^2(1)$ [p]	30.4 [.0000]	
Maximum land size (acres) = $\varphi(a)' = -b_1/(2*b_2) = 0$	24.5	1.84
N	617	

Instruments: owned land area and land area squared.

Sprayer Time and Weeding

Table 11
Estimates of Sprayer v, by Source

Country	India		United States
Source	ICRISAT Survey, 2009-2014	KrisanKraft Price List (2016)	Stiles and Stark (2016)
Estimation procedure	IV[a]	OLS	OLS
v	0.5802 (0.1200)	0.5209 (0.0605)	0.1458 (0.0789)
H_0: $v = 1$, F(1,x) [p]	χ^2=12.2 [0.0005]	F(1,2)= 62.8 [0.0156]	F(1,2)=117.1 [0.0084]
N	1,219	4	4
Village/year fixed effects	Y	N	N

[a]First-stage includes log of owned area and all land quality characteristics. Standard error clustered at the village/year level.

Sprayer Time and Weeding

Table 12
Elasticities for Changes in Area, v and Wage Rates on Sprayer Capacity (q), Sprayer Hours (m) and Weeding Labor Hours (l) for a Farm of Median Size (3 acres), from the Calibration and GMM Estimates

Coefficient	Point Estimate	Robust SE
dq/dv	-0.0498	0.0728
dm/dv	-0.233	0.113
dl/dv	0.0299	0.130
dq/da	0.297	0.0124
dq/dw	0.0292	0.0399
dm/dw	-0.756	0.977
dl/dw	-1.365	0.112

Summary

- Developed a model with fixed costs of labor and variation in machine capacity.
- Explains u-shaped relationship between profits per acre and land scale
- Support for mechanisms
  - Labor costs by acre
  - Consequences of rainfall variation
  - Sprayer usage and cost

Implications

Broader lessons

- When scale economies arise through costs may not be evident in production
- Fixed costs dependent on population dispersion, land equality, and labor-market thickness
- Ability to capture capacity scale depends on scale of available machines.
- Large machines may not be available if most farms are small.
- Agglomeration of small farms is made more difficulty by non-convexity of scale relationship.
- Workers and poor farmers may have a collective interest in not agglomerating due to effects on labor demand even when individually profitable.
- Consistent with evidence that agglomeration and scale is often triggered by exit of farmers and workers or major public interventions.