AJAE Appendix for:

Induced Innovation In U.S. Agriculture:

Time-series, Direct Econometric, and Nonparametric Tests

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Appendix A: Structure of the Direct Econometric Model

Let *A*, *M*, *L*, *K* represent the quantities of land, materials, labor, and capital, respectively, E_A, E_M, E_L, and E_K represent their factor augmentations. Suppose output (*Y*) is produced with a land input index, $X_A(E_A A, E_F M)$, and a labor input index, $X_L(E_L L, E_K K)$, according to a two-level production technology:

(A1) $Y_t = F_t[X_{A,t}(E_{A,t}A_t, E_{M,t}M_t), X_{L,t}(E_{L,t}L_t, E_{K,t}K_t)]$,

where $F_t(\cdot)$ is assumed to vary across time *t*.

We assume the production technology can be approximated by a two-level CES functional form (e.g., de Janvry et al. 1989; Thirtle et al. 2002):

(A2) $Y_t = [\gamma X_{A,t}^{-\rho} + (1-\gamma) X_{L,t}^{-\rho}]^{-1/\rho}$,

(A3) $X_{A,t} = [\alpha (E_{A,t}A_t)^{-\rho_1} + (1-\alpha)(E_{M,t}M_t)^{-\rho_1}]^{-1/\rho_1}$,

(A4) $X_{L,t} = [\beta (E_{L,t}L_t)^{-\rho_2} + (1-\beta)(E_{K,t}K_t)^{-\rho_2}]^{-1/\rho_2}$,

where $\alpha, \beta, \gamma, \rho, \rho_1, \rho_2$ are parameters and $\rho, \rho_1, \rho_2 > -1$.

The logarithms of the first-order conditions of profit maximization can be rearranged to give:

(A5) $\ln(A_t / M_t) = [1/(1+\rho_1)]\ln[\alpha/(1-\alpha)] - [1/(1+\rho_1)]\ln(P_{A,t}/P_{M,t}) - [\rho_1/(1+\rho_1)]\ln(E_{A/M,t})$

(A6) $\ln(L_t / K_t) = [1/(1+\rho_2)]\ln[\beta/(1-\beta)] - [1/(1+\rho_2)]\ln(P_{L,t}/P_{K,t}) - [\rho_2/(1+\rho_2)]\ln(E_{L/K,t})$

where P_A P_M, P_L, and P_K are the prices of land, materials, labor, and capital, respectively; $E_{A/M,t} = E_{A,t}/E_{M,t}$, and $E_{L/K} = E_{L,t}/E_{K,t}$.

Following Armanville and Funk (2003) and using notation (E_i) to represent the efficiency variables (factor augmentations), we define the IPF as the following set of instantaneous rates of factor augmentation ($(\hat{E}_{A,t},\ \hat{E}_{M,t}),(\hat{E}_{L,t},\hat{E}_{K,t})$) that producers can choose: [1]

(A7) $\{(\hat{E}_{A,t},\ \hat{E}_{M,t}),\ (\hat{E}_{L,t},\ \hat{E}_{K,t}\ ) : \hat{E}_{M,t} \le \phi_1(\hat{E}_{A,t}); \hat{E}_{K,t} \le \phi_2(\hat{E}_{L,t})\}$,

where the circumflexes (^) denote relative rates of change, i.e., $\hat{E}_{i,t} = (E_{i,t} - E_{i,t-1}) / E_{i,t-1}$; $\phi_1(\cdot)$ and $\phi_2(\cdot)$ are the first-level innovation possibility frontiers which are assumed to be differentiable, decreasing, strictly concave, and ellipses centered at (-1,-1), [2] i.e.,

(A8) $\phi_1(\cdot)$: $(\hat{E}_{A,t}+1)^2+n_{1,t}^2(\hat{E}_{M,t}+1)^2 = m_{1,t}^2$,

(A9) $\phi_2(\cdot)$: $(\hat{E}_{L,t}+1)^2+n_{2,t}^2(\hat{E}_{K,t}+1)^2 = m_{2,t}^2$,

where *n* is a slope parameter and *m* is a level parameter. The parameters *n* and *m* measure the augmentation trade-off rate between factors. The slopes of $\phi_1(\cdot)$ and $\phi_2(\cdot)$ with respect to E_A, and E_L, respectively, at given $(\hat{E}_{A,t},\ \hat{E}_{M,t})$ and $(\hat{E}_{L,t},\hat{E}_{K,t})$ are:

(A10) $-\phi_{1,t}' = -dE_{M,t} \big/ dE_{A,t} = (\hat{E}_{A,t}+1)/[n_{1,t}^2(\hat{E}_{M,t}+1)]$,

(A11) $-\phi_{2,t}' = -dE_{K,t} \big/ dE_{L,t} = (\hat{E}_{L,t}+1)/[n_{2,t}^2(\hat{E}_{K,t}+1)]$.

Generally, innovations can be viewed as activities that reallocate resources among factor augmentations for the purpose of profit maximization. The hypothesis of induced innovation is that a firm chooses a feasible set of factor augmentations on the IPF to maximize profit given the amount of employed factors (Funk 2002; Armanville and Funk 2003). Letting π denote profit, the firms' innovative decisions are made as follows:

(A12) $$\underset{\hat{E}_{A,t},\hat{E}_{M,t},\hat{E}_{L,t},\hat{E}_{K,t}}{\text{Max}} \{\hat{\pi}_t : \hat{E}_{M,t} \leq \phi_1(\hat{E}_{A,t}); \hat{E}_{K,t} \leq \phi_2(\hat{E}_{L,t})\},$$

given M_t, A_t, K_t, L_t and technology as defined in equation (A1). Since the constraint is always binding at the optimum, the first-order conditions of the maximization problem with respect to factor augmentations are:

(A13a) $\partial\hat{\pi}_t \big/ \partial\hat{E}_{A,t} = (\partial\hat{F}_t \big/ \partial X_{A,t})[\partial X_{A,t} / \partial(\hat{E}_{A,t} A_t)]A + \lambda_1\phi_1' = 0$

(A13b) $\partial\hat{\pi}_t \big/ \partial\hat{E}_{M,t} = (\partial\hat{F}_t \big/ \partial X_{M,t})[\partial X_{M,t} / \partial(\hat{E}_{M,t} M_t)]M_t - \lambda_1 = 0$

(A13c) $\partial\hat{\pi}_t \big/ \partial\hat{E}_{L,t} = (\partial\hat{F}_t \big/ \partial X_{L,t})[\partial X_{L,t} / \partial(\hat{E}_{L,t} L_t)]L + \lambda_2\phi_2' = 0$

(A13d) $\partial\hat{\pi}_t \big/ \partial\hat{E}_{K,t} = (\partial\hat{F}_t \big/ \partial X_{K,t})[\partial X_{K,t} / \partial(\hat{E}_{K,t} K_t)]K_t - \lambda_2 = 0$

Since the factor's marginal productivity is equal to its normalized price at instantaneous equilibrium, (A13a-d) yield:

(A14a) $-\phi_{1,t}' = (P_{A,t} A_t)/(P_{M,t} M_t) = \Phi_{1,t}$,

(A14b) $-\phi_{2,t}' = (P_{L,t} L_t)/(P_{K,t} K_t) = \Phi_{2,t}$.

Equations (A14a-b) specify the first-order curvature properties of the IPF required to satisfy the hypothesis of induced innovation. In this specification, the profit maximizer will choose the set of factor augmentations such that the slope of the IPF equals the relative input shares.

As demonstrated by Funk (2002), the hypothesis of induced innovation can be derived from a microeconomic model with fully rational firms. Suppose firms can make profits with an innovation chosen from their perceived IPF until this innovation is imitated by other firms. With the aggregate technology defined in (A2), the IPF defined in (A7), and profit-maximizing choice of innovations in a continuous-time setting,[3] the slopes of the IPF are:[4]

(A15) $-\phi'_{1,t} = [\alpha/(1-\alpha)]^{\sigma_1}[(P_{A,t}/E_{A,t})/(P_{M,t}/E_{M,t})]^{1-\sigma_1}$,

(A16) $-\phi'_{2,t} = [\beta/(1-\beta)]^{\sigma_2}[(P_{L,t}/E_{L,t})/(P_{K,t}/E_{K,t})]^{1-\sigma_2}$,

where $\sigma_1 = 1/(1+\rho_1)$ is the elasticity of substitution between land (*A*) and materials (*M*), and $\sigma_2 = 1/(1+\rho_2)$ is the elasticity of substitution between labor (*L*) and capital (*K*). Equations (A15-16) imply that, when the elasticity of substitution is greater (less) than one, an increase in efficiency-adjusted relative prices induces much (little) substitution between the factors given any technology. Thus, we get the surprising result that, after the substitution, it is more profitable to augment the intensively-used factor even if it is relative cheaper when the elasticity of substitution is greater than one (Armanville and Funk 2003). If the elasticity of substitution is less than one, we get the well-known result that it is more profitable to augment the relatively more expensive factor.

Consequently, one test for the IIH in this framework is to determine whether the bias of technical change is positively (negatively) correlated with relative prices in efficiency units (i.e., relative input shares) when the elasticity of substitution is greater (less) than one. For example, if the elasticity of substitution is less than one, the null hypothesis for testing the IIH in land (*A*) and materials (*M*) can be expressed as:

H_0: $corr(\hat{E}_{A,t} - \hat{E}_{M,t}, (P_{A,t}/E_{A,t})/(P_{M,t}/E_{M,t})) > 0$ or H_0: $corr(\hat{E}_{A,t} - \hat{E}_{M,t}, \Phi_{1,t}) > 0$

where *corr* denotes the correlation operator. Failure to reject the null hypothesis implies that the direction of producers' innovative decisions are guided by efficiency-adjusted relative prices as predicted by the IIH. Armanville and Funk (2003) labeled this directional test as a "weak" test of the IIH.

A "strong" test would determine whether quantitative innovation choices correspond to those predicted by the hypothesis, i.e., whether innovative behavior fully satisfies equations (A14a-b). Following Armanville and Funk (2003), a strong test can be developed from (A14a-b) by determining whether γ_1 and γ_2 equal 1 in the following specification of the slopes of the first-level innovation possibility frontiers:

(A17) $-\phi'_{1,t} = \Phi_{1,t}^{\gamma_1}$

(A18) $-\phi'_{2,t} = \Phi_{2,t}^{\gamma_2}$

That is, for the IIH to be strongly supported, the elasticity of the slopes of $\phi_1(\cdot)$ and $\phi_2(\cdot)$ with respect to relative input shares must be 1.

From equations (A10-11) and (A17-18), we derive the following relationships: [5]

(A19) $E_{A,t} / E_{M,t} = (E_{A,0} / E_{M,0}) \prod_{s=1}^{t} n_{1,s}^2 \Phi_{1,s}^{\gamma_1}$

(A20) $E_{L,t} / E_{K,t} = (E_{L,0} / E_{K,0}) \prod_{s=1}^{t} n_{2,s}^2 \Phi_{2,s}^{\gamma_2}$

Intuitively, the relative factor productivities at time *t* depend on past values of the slope parameter n_i, past values of the relative input shares, and the relative productivities at the starting period.

By substituting (A19-20) into (A5) and (A6), respectively, we obtain:

(A21) $\ln \frac{A_t}{M_t} = \frac{1}{1+\rho_1} \ln \frac{\alpha}{1-\alpha} - \frac{1}{1+\rho_1} \ln \frac{P_{A,t}}{P_{M,t}} - \frac{\rho_1}{1+\rho_1} \left(\gamma_1 \sum_{s=1}^{t} \ln \Phi_{1,s} + 2 \sum_{s=1}^{t} \ln n_{1,s} + \ln \frac{E_{A,0}}{E_{M,0}} \right)$

$$\text{(A22)} \quad \ln\frac{L_t}{K_t} = \frac{1}{1+\rho_2}\ln\frac{\beta}{1-\beta} - \frac{1}{1+\rho_2}\ln\frac{P_{L,t}}{P_{K,t}} - \frac{\rho_2}{1+\rho_2}\left(\gamma_2\sum_{s=1}^{t}\ln\Phi_{2,s} + 2\sum_{s=1}^{t}\ln n_{2,s} + \ln\frac{E_{L,0}}{E_{K,0}}\right)$$

Since data are available for factor prices and the relative input shares (Φ_1 and Φ_2), the relative demand equations (A21-22) can be estimated if slope parameters n_1 and n_2 are specified. Instead of following Armanville and Funk (2003) in making the *n*'s a function only of time, we treat them as functions of innovation investments, including public research R_{pub}, private research R_{pri}, and extension *Ext*:

$$\text{(A23)} \quad \ln(n_{j,t}) = \delta_{j,1}\ln(R_{pri,t}) + \delta_{j,2}\ln(R_{pub,t}) + \delta_{j,3}\ln(Ext_t) \;\; (j = 1, 2),$$

where δ_{ji} (j = 1, 2; i = 1, 2, 3) is a constant.

Assuming that innovation investments are allocated evenly for factor augmentation at the starting period, i.e., $E_{A,0} / E_{M,0} = 1$ and $E_{L,0} / E_{K,0} = 1$, rewriting equations (A21-22) gives equation (3.3) in the paper.

Appendix B: Nonparametric Tests

Under the translating hypothesis, i.e., $X_i = x_i + B_i$, the weak axiom of profit maximization (WAPM) is equivalently written as:

(B1) $\mathbf{P}_t'\mathbf{x}_t \geq \mathbf{P}_t'\mathbf{x}_s,\ \forall s,t \in T$, or

(B2) $\mathbf{P}_t'(\mathbf{X}_t - \mathbf{B}_t) \geq \mathbf{P}_t'(\mathbf{X}_s - \mathbf{B}_s),\ \forall s,t \in T$,

where $\mathbf{x_t}$, $\mathbf{x_s}$, $\mathbf{X_t}$, and $\mathbf{X_s}$ are effective and actual netput vectors at observations *t* and *s*, and $\mathbf{B_t}$ and $\mathbf{B_s}$ are the augmentation vectors at the respective observations. If the data satisfy the WAPM, there exists a closed, convex, and negative monotonic production possibilities set that rationalizes the data in *T*, and there exists a profit-maximizing output supply and input demand solution. The WAPM specified in equation (B2) also allows us to recover the technology in the presence of technical change given the data observations. If $B_{i,t} > B_{i,s}$ for an input, technical change between *s* and *t* is *i*th-input saving. In another words, to achieve the same level of effective input at time *t* as in time *s* requires a smaller quantity of the *i*th-input. If $B_{i,t} > B_{i,s}$ for outputs, technical change between *s* and *t* is output augmenting. For the same actual level of all inputs, more output is produced at time *t* than in time *s*.

We follow Chavas et al. (1997) in specifying three augmentation restrictions needed to conduct nonparametric testing of the IIH. The first restriction specified in equation (3.5) in the text, treats the technology indices as functions of a constant term and a weighted sum of a finite lag of past innovation investments. The idea for this model specification is that R&D investments can generate technical progress, and the process of technical change takes time. Also the Hicksian IIH emphasizes the crucial role of relative price changes in determining the direction of research investments towards augmenting particular factors, which suggests that the marginal impact of R&D depends on relative prices. Thus, it provides an approach to directly investigate the Hicksian IIH.

The second restriction – smoothing restriction on the output augmentation variables has the following expression:

(B3) $$B_{y,t} \geq (\sum_{j=1}^{c} B_{y,t-j}) / c$$

This restriction requires output augmentation to be at least as large as a moving average of previous values, so augmentation is not permitted to trend downward over time. The moving average allows for weather to dampen output augmentation in individual years. Following Chavas et al. (1997), we used a 5-year moving average.

The third restriction assumes nonnegativity of the marginal effect of innovation activities on augmentation indices:

(B4) $\partial B_{i,t} / \partial R_{t-j} = \beta_{i,j} + (P_{i,t-j} - 1)\gamma_{i,j} \geq 0,\ i = A, M, L, K,\ \ j = 1, \cdots, r_i$, and

(B5) $\partial B_{y,t} / \partial R_{t-j} = \beta_{y,j} \geq 0,\ \ j = 1, \cdots, r_y$.

In the last step, these parameters are estimated by solving a quadratic programming problem. The intuition is to make the augmentation indices and the impact of exogenous shifters "as close to the data as possible" while satisfying the WAPM. Based on the estimates of these parameters, the induced innovation hypothesis and the nature of technical change in U.S. agriculture are examined.

Appendix C: Construction of Input Price Proxies for the Period 1932-1959

Using prices for machinery and fertilizer from the Thirtle et al. (2002) data set to represent prices of capital and materials, respectively, we indexed both Ball's and Thirtle et al.'s U.S.-level data sets to Ball's (2004) state-level series in the following way: First, we computed averages of Ball's and Thirtle et al.'s U.S. prices for each input category for the first five years in the Ball series, 1948-1952. Second, we merged Thirtle et al.'s prices for each input category into Ball's U.S. series by multiplying Thirtle *et al*.'s U.S. prices series for 1932-1947 by the ratio of Ball's and Thirtle et al's U.S. average prices for 1948-1952 and denote it the Ball-TST data set. Third, we computed averages of each state-level price series and of Ball's U.S. prices for the first five years of the state-level series, 1960-1964. Lastly, we spliced the Ball-TST U.S. prices with the state-level series by multiplying the Ball-TST data for 1932-1959 by the ratio of the state average to the U.S. average price in 1960-1964 for each state and input.

Appendix D: Additional Empirical Results

Table D.1. Reverse Causality Test Results [a]

		$LnP_{A/M}$		LnR_{pri}		LnR_{pub}		$LnExt$	
Number of lags	Causal variable	Estimated Coefficient	Standard Error	Estimated Coefficient	Standard Error	Estimated Coefficient	Standard Error	Estimated Coefficient	Standard Error
1	$LnR_{A/M,t-1}$	-0.6645*	0.0450	0.0013*	0.0003	-0.0041*	0.0006	0.0049	0.0067
2	$LnR_{A/M,t-1}$	-0.7067*	0.0546	0.0004	0.0006	-0.0091*	0.0012	-0.0130	0.0141
	$LnR_{A/M,t-2}$	0.0467	0.1043	0.0008	0.0011	-0.0064*	0.0023	-0.0190	0.0270
3	$LnR_{A/M,t-1}$	-1.2086*	0.1519	0.0002	0.0013	-0.0105*	0.0023	-0.0073	0.0275
	$LnR_{A/M,t-2}$	-0.0155	0.1853	0.0012	0.0015	-0.0090*	0.0028	-0.0090	0.0333
	$LnR_{A/M,t-3}$	-0.0633	0.1584	-0.0007	0.0014	0.0066*	0.0025	-0.0135	0.0296
		$LnP_{L/K}$		LnR_{pri}		LnR_{pub}		$LnExt$	
Number of lags	Causal variable	Estimated Coefficient	Standard Error	Estimated Coefficient	Standard Error	Estimated Coefficient	Standard Error	Estimated Coefficient	Standard Error
1	$LnR_{L/K,t-1}$	0.0325	0.0417	-0.0007	0.0005	0.0027*	0.0010	0.0043	0.0121
2	$LnR_{L/K,t-1}$	0.0239	0.0492	-0.0010	0.0006	0.0039*	0.0014	0.0051	0.0148
	$LnR_{L/K,t-2}$	0.0400	0.8187	-0.0013*	0.0006	0.0028*	0.0014	0.0032	0.0147
3	$LnR_{L/K,t-1}$	0.0600	0.0574	-0.0008	0.0007	0.0034*	0.0017	0.0065	0.0173
	$LnR_{L/K,t-2}$	-0.1303*	0.0617	-0.0012	0.0007	0.0033	0.0018	0.0062	0.0186
	$LnR_{L/K,t-3}$	0.0117	0.0605	-0.0003	0.0007	0.0029	0.0018	0.0104	0.0184

[a] The optimal lag selected by the AIC was 1 in all equations. The critical t-values for these 2-tailed tests are 1.96 at the 0.05 significance level. Significant coefficients are identified by an asterisk.

Table D.2. Estimated Direct Econometric Model with Innovation Stock Variables [a]

Land-Materials Equation			Labor-Capital Equation		
Variable	Coefficient	Standard Error	Variable	Coefficient	Standard Error
Constant	-3.15843*	0.58782	Constant	1.85184*	0.29837
$\mathrm{Ln}P_{A/M}$	-0.47584*	0.03620	$\mathrm{Ln}P_{L/K}$	-0.11052*	0.04397
F_1	-0.00016*	0.00003	F_2	0.01877*	0.00250
$\ln R_{pri}$	0.22049*	0.04697	$\ln R_{pri}$	-0.03164	0.03252
$\ln R_{pub}$	-0.16710*	0.01802	$\ln R_{pub}$	0.00277	0.01439
$\ln Ext$	-0.07618	0.05493	$\ln Ext$	-0.05388	0.03966
$\overline{R}^2$ [b]	0.51445		$\overline{R}^2$	0.10301	
Hypothesis	Tested Null	Statistic	Hypothesis	Tested Null	Statistic
Weak Test, $\gamma_{A/M} > 0$	$\gamma_{A/M} \leq 0$	-4.382	Weak Test, $\gamma_{L/K} > 0$	$\gamma_{L/K} \leq 0$	7.215*
Strong Test, $\gamma_{A/M} = 1$	$\gamma_{A/M} = 1$	209.403*	Strong Test, $\gamma_{L/K} = 1$	$\gamma_{L/K} = 1$	421.587*

[a] Critical values at the 0.05 significance level are 1.96 for the 2-tailed t-ratios on the coefficients, 1.65 for the 1-tailed standard normal statistics for the weak test, and 3.84 for the 1-tailed Wald chi-square statistics for the strong test. Significant coefficients are identified by an asterisk.

[b] $\overline{R}^2$ is an average of state-specific adjusted R-square values.

Appendix E: Marginal Cost of Developing and Implementing Input-Saving Technologies

All tests of the IIH conducted to date have only tested the demand side of the hypothesis. That includes ours. Although both Binswanger (1974) and Olmstead and Rhode (1993) acknowledged the demand-side nature of the hypothesis tests, most others who have tested the IIH have been silent about this important limitation (Coxhead 1997, is an exception). [6] All tests of the hypothesis have implicitly maintained the hypothesis that the marginal cost of developing and implementing technologies that save one input is the same as the marginal cost of saving an equal percent of any other input. Since it is highly unlikely that innovation possibilities are this neutral, it is possible that the IIH is in fact a valid explanation and yet producers augment cheaper factors because the marginal costs of developing and implementing input-saving technologies for the relatively expensive inputs are greater than for the relatively cheap ones. That is, technical change may not bias toward saving a particular input even when it tends to be relatively expensive. Unfortunately, data on the development and implementation costs of various input-saving technologies are lacking.

Having failed to find support for the IIH relying exclusively on the demand for innovation and lacking essential data to distinguish differences in innovation supply, we calculated relative differences in the marginal costs of developing and implementing saving technologies for the various inputs to be consistent with the hypothesis. The qualitative pairwise results of these nonparametric computations are reported for nine representative states in Table E.1.

For differences in marginal costs of technology development and implementation to have rendered the data consistent with the IIH, sufficient conditions included higher marginal costs of land- and capital-saving technologies than of material-saving technologies in nearly all states.[7] This finding was robust across the various types of input-saving innovation investment. If these marginal cost differences actually existed, then the higher cost of developing and implementing land- or capital-saving technologies could have induced profit-maximizing technical change that was biased toward augmenting materials rather than land or capital even when land and capital were the relatively more expensive inputs.

For consistency with the IIH, another condition included a higher marginal cost of developing and implementing land-saving technology than of labor-saving technology in most states for all types of innovation investment. Another condition was a higher marginal cost of land-saving technology than of capital-saving technology in all states for research investments and in a majority of states for extension investments. This same observation also applies in nearly all states for labor vs. material-saving technologies. However, the order ranking of sufficient marginal cost differences for labor and capital was less clear. For private research investments, higher marginal costs for labor-saving technology than for capital-saving technology were implied in 2/3 of the states. Nearly the reverse was found for extension investments, and neither dominated for public research investments.

Table E.1. Nonparametric Estimates of Relative Marginal Cost of Developing and Implementing Input-Saving Technology Required for Consistency with the Induced Innovation Hypothesis [a]

Input Pair	Marginal Cost Relationship	Input-Saving Innovation Investments		
		R_{pri}	R_{pub}	*Ext*
Land vs. materials	$MC_A > MC_M$	CA, FL, IA, KS, MI, NC, NY, TX, WA	CA, FL, IA, KS, MI, NC, NY, TX, WA	CA, FL, IA, KS, MI, NC, NY, TX, WA
Labor vs. capital	$MC_L > MC_K$	CA, FL, KS, NY, TX, WA	CA, FL, KS, TX, WA	CA, KS, WA
	$MC_L = MC_K$			FL
	$MC_L < MC_K$	IA, MI, NC	IA, MI, NC, NY	IA, MI, NC, NY, TX
Land vs. capital	$MC_A > MC_K$	CA, FL, IA, KS, MI, NC, NY, TX, WA	CA, FL, IA, KS, MI, NC, NY, TX, WA	CA, KS, NC, NY, WA
	$MC_A = MC_K$			FL, IA, MI,TX
Labor vs. materials	$MC_L > MC_M$	CA, FL, IA, KS, NC, NY, TX, WA	CA, FL, IA, KS, NC, TX, WA	CA, FL, IA, KS, WA
	$MC_L < MC_M$	MI	MC, NY	MI, NC, NY, TX

Land vs. labor	$MC_A > MC_L$	CA, IA, KS, MI, NC, NY, TX, WA	IA, MI, NC, NY, WA	IA, MI, NC, NY, TX, WA
	$MC_A = MC_L$	FL	FL	FL, KS
	$MC_A < MC_L$		CA, KS, TX	CA
Capital vs. materials	$MC_K > MC_M$	CA, FL, IA, KS, NC, TX, WA	CA, FL, IA, KS, MI, NC, NY, TX, WA	CA, FL, IS, KS, MI, NC, TX, WA
	$MC_K < MC_M$	MI, NY		NY

[a] Codes: R_{pri} is private research investments, R_{pub} is public research investments, *Ext* is extension investments. MC_i represents marginal cost of developing and implementing input-saving technologies for input *i*.

Footnotes

[1] When the producers simultaneously choose all four factors to maximize profit, the IPF should be defined as the following set: $\{(\hat{E}_{A,t}, \hat{E}_{M,t}, \hat{E}_{L,t}, \hat{E}_{K,t}) \mid \hat{E}_{A,t} \leq \phi(\hat{E}_{M,t}, \hat{E}_{L,t}, \hat{E}_{K,t})\}$. However, this four-dimensional innovation possibility frontier proves to be intractable for empirical application. By maintaining weak separability between (*A, M*) and (*K, L*), the two-level production technology facilitates empirical testing of the IIH.

[2] The assumption that the IPF is centered at (-1, -1) is imposed to assure that the slope of the IPF at the axis points is finite and nonzero (Armanville and Funk 2003).

[3] In this case, the length of the period between innovation and imitation tends to zero.

[4] See Funk (2002) for details and discussion of the derivation.

[5] Combining equation (B10-11) and (B17-18) and noting that $\hat{E}_{i,t} + 1 = E_{i,t} / E_{i,t-1}$ ($i = M, A, K, L$) gives:

$(E_{A,t} / E_{A,t-1})/(E_{M,t} / E_{M,t-1}) = n_{1,t}^2 \Phi_{1,t}^{\gamma_1}$ and $(E_{L,t} / E_{L,t-1})/(E_{K,t} / E_{K,t-1}) = n_{2,t}^2 \Phi_{2,t}^{\gamma_2}$, $\forall t$. By substituting backward until $t = 1$, we obtain equation (B19-20).

[6] Binswanger (1974, p. 975) wrote, “But despite that price rise, technical change was machinery-using, not saving. Had innovation possibilities been neutral, this could not occur.” From Olmstead and Rhode (1993, p. 110), “…the evolving structure of American agriculture cannot be explained simply in terms of the relative supplies and prices of a

few factors.…The induced innovation hypothesis puts too many eggs in the demand-side basket."

[7] The cost shares averaged across states and years for materials (45%) is greater than for labor (23%), which in turn is greater than for capital. Among the 4 inputs, the average cost share for land is the smallest (13%).

Additional References

Coxhead, I. 1997. "Induced Innovation and Land Degradation in Developing Country Agriculture." *The Australian Journal of Agricultural and Resource Economics* 41(2):305-32.