Technology Spillovers and Land Use Change: Empirical Evidence from Global Agriculture

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Motivation

- **Borlaug's hypothesis**: Technological progress has the potential to reduce deforestation by increasing production in current croplands.
- **Jevons' paradox**: Technological progress increases land rents, which enncourage more land conversion to agriculture, thus accelerating deforestation (Angelsen et al., 2001).
- Such seemingly contradictory effects underpin skepticism about the desirability of investments in agricultural research and development (R&D) (Rudel et al., 2009).

When does technological change promote deforestation?

Two critical issues:

- The elasticity of demand faced by producers in the innovating region. Elastic demand leads to land expansion.
- Spillovers—or land use *leakage*—from the innovating region onto other regions.

Knowledge Gap:

Despite theoretical insights, we lack comprehensive empirical evidence on the effects of technological progress on land use.

Existing Empirical Evidence Supports Jevon's Paradox

- A large number of studies find support for Jevon's paradox.
- Most of these studies are highly localized (see Angelsen et al., 2001).
- There are few cross-country studies (Barbier and Burgess, 2001; Rudel et al., 2009; Ewers et al., 2009):
  - Fail to control for other drivers of area growth (e.g., increases in demand).
  - There is not a counterfactual against to which the effects of technology (yields) can be measured.
  - Ignore spillover effects.
  - Technology is measured by yields, confounding intensification with growth in productivity.

This paper:

- Develops a unified framework that considers the effects of domestic and foreign technological change while controling for other drivers of cropland, such as changes in non-land input prices, land rents, and demand for agricultural goods.
- The measure of technology are changes in Total Factor Productivity (TFP).
- We answer two critical questions:
  - **Does technological progress reduce cropland expansion?**
  - **How does agricultural technological progress in a given region influence land use changes in other regions?**

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Preliminaries:

- Home region produces an agricultural good which is consumed domestically and also exported to other j countries.
- The j countries also produce the agricultural good, consume it, and may engage in trade. (Home $\in j$.)
- 4 building blocks: technology and prices, demand, supply and equilibrium.
- In what follows all the model equations are in relative changes. E.g., $x = dX/X$ is the relative change in X.

Technology and prices

The relative change in the price of farm output produced by country, p_i, is given by:

$$p_i = (1 - \lambda_i) r_i + \lambda_i w_i - z_i. \tag{1}$$

where:

- λ_i is the share of non-land inputs in total production costs.
- r_i and w_i are relative changes in land and non-land input prices.
- z_i is the relative change in TFP.

Constant Elasticity of Substitution (CES) preferences

Relative change in total demand for i's products, q_i^D:

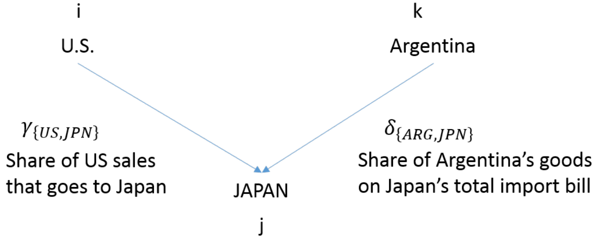
$$q_i^D = \overbrace{\underbrace{\sum_j^N \gamma_{ij} d_j}_{\substack{\text{Changes in demand, } d_j\text{,} \\ \text{in destination markets} \\ \text{weighted by} \\ \text{sales shares, } \gamma_{ij}.}}}^{\text{Expansion Effect}} - \sigma \overbrace{\left[\sum_k \underbrace{\omega_{ik}\left(p_i - p_k\right)}_{\substack{\text{When } p_i > p_k \\ q_i^D \text{ decreases} \\ \text{according to} \\ \omega_{ik} = \sum_j \gamma_{ij}\delta_{kj} \\ \delta_{k,j} \text{ are j's budget shares}}} \right]}^{\text{Substitution Effect}}. \qquad (2)$$

σ is the Armington elasticity of substitution across suppliers.

Sales shares: γ_{ij} is how much of country i's total sales are sold in market j.
Budget shares: δ_{kj} is how much of j's consumption comes from supplier i.
Competition indices: Summarize the strength of competition between i and any other supplier k across all the j destination markets:

$$\omega_{ik} = \sum_j \gamma_{ij}\delta_{kj}.$$

Example:



$$\omega_{\{US,ARG\}} = \gamma_{\{US,JPN\}} \times \delta_{\{ARG,JPN\}}$$

10 largest competition indexes, 2001-10

i	k	ω_{ik}	ω_{ki}
Mexico	United States	0.32	0.06
Costa Rica	United States	0.25	0.00
Brunei Darussalam	Malaysia	0.25	0.00
Portugal	Spain	0.25	0.03
Panama	United States	0.24	0.00
Honduras	United States	0.24	0.00
Belarus	Russian Federation	0.22	0.02
Dominican Republic	United States	0.22	0.00
Nicaragua	United States	0.20	0.00
Guinea-Bissau	India	0.18	0.00

We now use (1) to write the output prices in (2) in terms of the TFP shifters, land rents, and non-land input prices. After rearranging:

$$q_i^D = \sum_{j}^{M} \gamma_{ij} d_j - \sigma_i \left[\sum_{k \neq i}^{N-1} \omega_{ik} \left(z_k - z_i \right) \right] - \ldots . \tag{3}$$

which makes clear that the demand for output produced in i depends on changes in TFP in country i relative to every partner...

For instance, if country k's TFP increases faster than country i's, country k becomes more competitive ($p_k < p_i$) displacing country i in the different markets where i and k compete.

Supply

Assume a CES production function. *Equilibrium* demand for land in terms of output, TFP, and non-land input prices, l^*:

$$l^* = \left[\underbrace{(q_i^S - z_i)}_{\substack{\text{Expansion}\\ \text{Effect}}} + \underbrace{\lambda \overbrace{\phi}^{\substack{\text{Input}\\ \text{Substitution}\\ \text{Elasticity}}} w_i}_{\substack{\text{Substitution}\\ \text{Effect}}} \right] H. \tag{4}$$

where $H = \nu_i(\nu_i + \lambda_i \phi_i)^{-1}$.

Optimal demand for land

In equilibrium, $q_i^S = q_i^D$, so we can substitute (3) for q_i^S in (4) to get the optimal demand for land in terms of both supply and demand factors:

$$l_i^* = \left[\lambda_i \phi_i w_i - z_i + \sum_j^M \gamma_{ij} d_j - \sigma_i \left(\sum_{k \neq i}^{N-1} \omega_{ik} \left(z_k - z_i \right) + \lambda_i \sum_{k \neq i}^{N-1} \omega_{ik} \left(w_i - w_k \right) + (1 - \lambda_i) \sum_{k \neq i}^{N-1} \omega_{ik} \left(r_i - r_k \right) \right) \right] H_i \quad (5)$$

This is a linear equation whose parameters can be estimated using data on land use, TFP growth, land rents, non-land input prices, and changes in demand.

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Estimating equation

$$
\begin{aligned}
l_{it}^{*} = {} & \beta_1 z_{it} + \beta_2 \sum_{k}^{m} \omega_{ikt}(z_{kt} - z_{it}) + \beta_3 w_{it} \\
& + \beta_4 \sum_{k}^{m} \omega_{ikt}(r_{it} - r_{kt}) + \beta_5 \sum_{k}^{m} \omega_{ikt}(w_{it} - w_{kt}) \\
& + \beta_{6[D]}\gamma_{iit} d_{it} + \beta_{6[F]} \sum_{j \neq i}^{n-1} \gamma_{ijt} d_{jt} + \beta_7 \bar{L}_i + \mu_i + \varepsilon_{it}.
\end{aligned} \tag{6}
$$

with $\beta_1 = \lambda\phi\frac{\nu}{\nu+\phi\lambda}$, $-\beta_2 = \beta_3 = \frac{\nu}{\nu+\phi\lambda}$ and so forth.
Expected signs: $\beta_3, \beta_6 > 0$, rest < 0.

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Data

Pooled cross sections: 70 countries ($\approx$ 75% of global cropland), 2 periods —annual growth rates during 1991-00 and during 2001-10 — sourced from:

- Cropland, FAO.
- w, proxy: implicit fertilizer prices using Fuglie (2012)'s growth accounting framework.
- z, Decennial changes in Agricultural Total Factor Productivity from Fuglie 2012.
- d, proxy GDP per capita (WBDI).
- r, Implied land rents from growth accounting (Fuglie 2012).
- ω_{ik}, built with production and consumption from FAOSTAT; bilateral exports from GTAP.
- $\bar{L}$: FAOSTAT's cropland at the beginning of each decade over the total land that is suitable for agriculture as defined in Ramankutty et al. (2002).

Table: Regression results.

	Dependent variable:		
	Decade-Specific Annual Cropland Growth Rate		
	(1)	(2)	(3)
Own TFP β_1	-0.357^{***}	-0.408^{***}	-0.595^{***}
	(0.125)	(0.134)	(0.207)
Relative TFP β_2	-1.414^{***}	-1.480^{***}	-1.939^{***}
	(0.333)	(0.340)	(0.552)
Fertilizer price β_3	0.079^{***}	0.078^{***}	0.068^{***}
	(0.026)	(0.024)	(0.026)
Relative land rents β_4	-1.199^{***}	-1.200^{***}	-1.167^{***}
	(0.191)	(0.191)	(0.195)
Relative fert. price β_5	-0.148^{*}	-0.153^{*}	-0.107
	(0.083)	(0.080)	(0.085)
Sales-share weighted per capita GDP β_6	0.162^{*}		0.175^{**}
	(0.086)		(0.085)
Dom. GDP per capita $\beta_{6[D]}$	-0.072^{***}	-0.076^{***}	-0.077^{***}
	(0.020)	(0.021)	(0.020)
For. GDP per capita $\beta_{6[F]}$	-0.001^{*}	-0.001^{*}	-0.001^{**}
	(0.0004)	(0.0004)	(0.0004)
Cropland share β_7		0.122	
		(0.080)	
Forest area		0.737^{**}	
		(0.298)	
Cropland share $\times$ Own TFP			0.501^{*}
			(0.300)
Cropland share $\times$ Relative TFP			1.133
			(0.734)
Observations	140	140	140
R^2	0.384	0.411	0.395
Adjusted R^2	0.170	0.179	0.169
Note:			*p<0.1; **p<0.05; ***p<0.01

OLS estimates using country fixed effects; standard errors robust to heterokedasticity.

Jevons' Paradox or Borlaug's Hypothesis?

Elasticity of cropland expansion w.r.t. own-TFP growth:

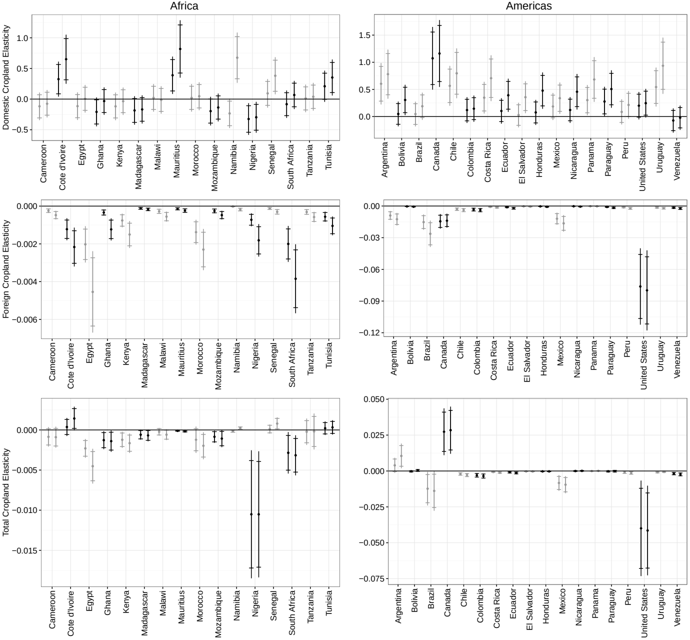
$$\frac{l_{it}}{z_{it}} = -0.357 + 1.414 \sum_{k}^{m} \omega_{ik}.$$

- If $\sum_k^m \omega_{ik} = 0$, a 1% *increase* in own decennial TFP growth *reduces* own decennial cropland growth by 0.35%. (BH)
- For $\sum_k^m \omega_{ik} > 0.25$, TFP growth encourages land expansion. (JP)

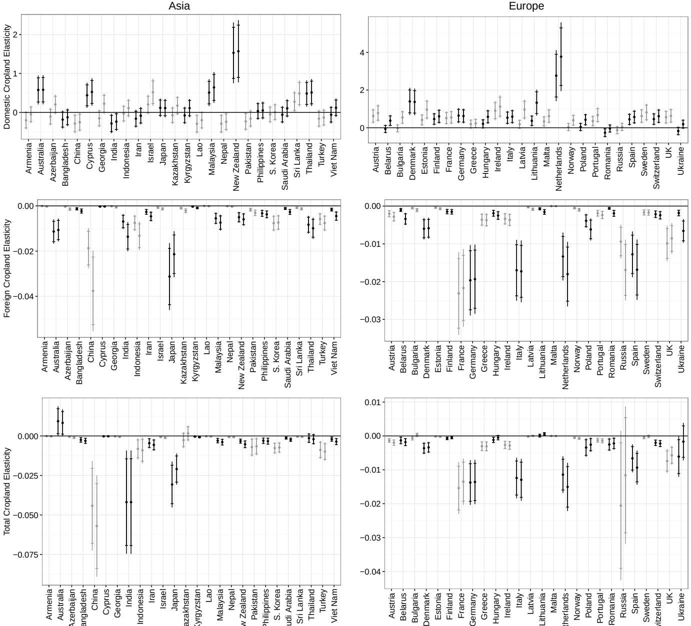
Moreover, increases in TFP growth in a foreign country reduce the domestic demand for land in proportion to the size of the bilateral competition index:

$$\frac{l_{it}}{z_{kt}} = -1.414\omega_{ik}.$$

Domestic, Foreign and Total TFP Cropland Elasticities w.r.t TFP (I), 1991-2000 and 2001-2010



Domestic, Foreign and Total TFP Cropland Elasticities w.r.t TFP (II), 1991-2000 and 2001-2010

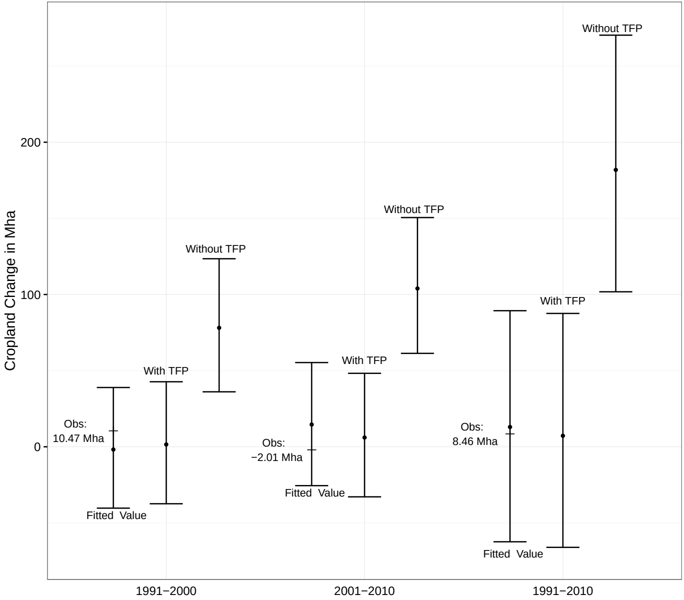


Demand vs. Technology

- Was ag. technological progress been large enough to counteract the cropland expansion caused by demand growth during 1991-2010?

- We can use the parameter estimates to explore this question using in-sample predictions that isolate the effects of growth in TFP and per capita GDP as well as their interaction.

Simulated global cropland change with and without TFP growth



Conclusions

- **Direct land use effects:** In most countries of the world, TFP growth is either uncorrelated or is positively associated with cropland expansion.
- Yet, because of **indirect land use effects**, worldwide patterns of TFP growth have been an important source of global land savings.
- We estimate that in the absence of TFP growth, global land expansion from 1991 to 2010 would have been significantly larger than observed.
- The divergence between the country-level and the global results is explained by the changes in production patterns as countries interact in international markets.

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Cropland elasticities w.r.t TFP in terms of the elasticity of demand

After eliminating the output term q_i^S, we can show that the effect of TFP growth on cropland depends on the size of the elasticity of demand for aggregate output facing producers in country i:

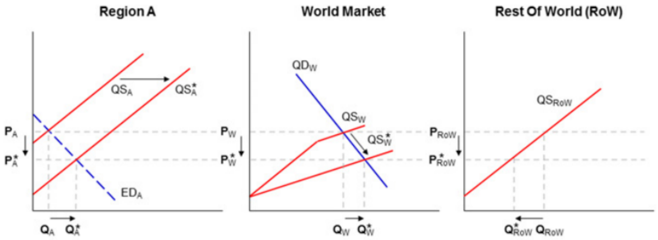
$$l_i^*(z_i)^{-1} = H_i \left(|\eta_i^D| - 1 \right).$$

Moreover, increases in TFP growth in a foreign country reduce the domestic demand for land in direct proportion to the size of the bilateral competition index:

$$l_i^*(z_k)^{-1} = -H_i \sigma_i \omega_{ik}.$$

Spillovers, or land use *leakage*, from the innovating region onto other regions

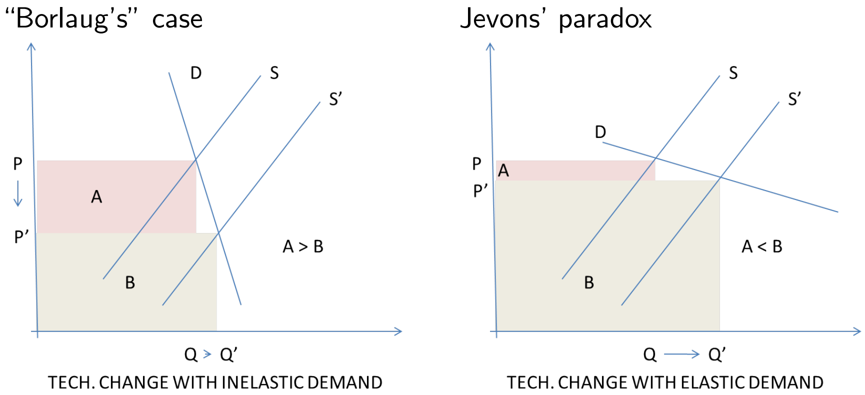
- Leakage is the global, indirect, land use effect of a localized innovation, that occurs as supply responses are interlinked through international trade.



Adapted from Hertel, Ramankutty, and Baldos (2014).

- Leakage is important because, even if localized TFP growth encourages regional land expansion, regional deforestation may be offset as pressure on forests is relieved in other parts of the world.

The elasticity of demand faced by producers in the innovating region



- Technological change shifts expected supply outward
- With elastic demand, the product $P \times Q$, expected income, increases
- The use of farm-owned factors will then increase
- With inelastic demand, expected income shrinks, discouraging use of land, labor, etc.
- Adapted from Chavas and Helmberger (1996)

Global effects of TFP

- β_1 is the global elasticity of cropland w.r.t. a global, uniform change in TFP.
- Illustrative counterfactual:
  - Average TFP growth during 2001-2010 $\approx 16\%$
  - $\beta_1 = -0.35$, cropland in 2010 $\approx 1{,}344$ Mha
  - Under past-decade TFP growth, current worldwide cropland would decline by a point estimate of 70 Mha, (95% CI within 18-122 Mha.)
- For a perspective, consider that the forested area of Malaysia is around 20.5 Mha, Indonesia is 95.5 Mha and the Amazon is 550 Mha.