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

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**Abstract**

The existing evidence for the effects of agricultural technological change on cropland use is inadequate to clarify the polarized views on whether encouraging technological progress would slow down the expansion of croplands into forests. This article seeks to inform these views by developing and estimating a model that links the changes in a country's cropland to the changes in both domestic and foreign total factor productivity (TFP). We find that in most countries of the world, TFP growth is either uncorrelated or is positively associated with cropland expansion. Yet worldwide patterns of TFP growth have been an important source of global land savings. The divergence between the country-level and the global results is explained by the changes in production patterns as countries interact in international markets. Based on our findings, we estimate that in the absence of TFP growth, global cropland expansion from 1991 to 2010 would have been twice as large as observed.

**Keywords:** Deforestation, Land Use Change, International Trade, Total Factor Productivity, Global Agriculture, Agricultural Technology.

**JEL Codes:** Q15 (Land Use), Q16 (R&D, Agricultural Technology), Q24 (Land), Q56 (Environment and Trade).

## 1 Introduction

Technological progress is a central component of any viable strategy that seeks to increase the supply of agricultural goods while improving the sustainability of the world food system (Godfray et al., 2010; Tilman et al., 2011). Conventional wisdom holds that technological progress has the potential to reduce or slow down deforestation by decreasing the land needed

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to produce a given amount of agricultural goods. Yet, under some circumstances, technological progress can actually accelerate deforestation(Angelsen et al., 2001; Hertel, Ramankutty, and Baldos, 2014). Such seemingly contradictory effects have given rise to skepticism about the desirability of investments in agricultural research and development (R&D) as a way of decreasing the land use footprint of agriculture (Rudel et al., 2009; Ewers et al., 2009; Phelps et al., 2013; Carrasco et al., 2014).

Conceptually, the effects of technological progress on land use are well understood. Technological progress will encourage cropland expansion only if the demand faced by producers is price elastic (e.g., Chavas and Helmberger, 1996; Angelsen et al., 2001); when this condition is met, the extent of land expansion will depend on the land scarcity as well as on the available technologies (Chavas and Helmberger, 1996; Hertel, Ramankutty, and Baldos, 2014). And even if technological progress leads to increased deforestation in the innovating country, the interdependence of local land use decisions as countries interact in international markets may result in decreased deforestation elsewhere (Hertel, Ramankutty, and Baldos, 2014).

Notwithstanding the insights provided by theory, we lack solid empirical evidence on either the effects of agricultural technological progress on country-level cropland expansion, or on the international interdependence in land use patterns associated with technological progress. To be sure, there is a rich body of research on the effects of the adoption of specific technologies in the production of different commodities in different ecosystems (see Villoria, Byerlee, and Stevenson, 2014, for a recent review of the literature). For the most part, these studies have found that the introduction of new technologies has not led to increased conservation of the land resources. There are also a number of studies that have looked at correlations between area changes in yields and harvested areas in the cross-section of countries (Barbier and Burgess, 2001; Ewers et al., 2009; Rudel et al., 2009). These studies find scant support for the notion that yield growth is associated with reductions in cropland. A difficulty facing some of these studies is the lack of a clear counterfactual against to which the effects of technological progress, as proxied by yields, can be measured (Hertel, Ramankutty, and Baldos, 2014). In sharp contrast, on a global level, the evidence indicates that most of the world's growth in cereal output has come fundamentally from technological progress (Johnson, 2000). Studies of the Green Revolution based on partial and general equilibrium simulation models by Evenson and Rosegrant (2003) and Stevenson et al. (2013), support this assertion.

The objective of this article is to measure the effects of technological progress in agriculture on cropland expansion at various geographical resolutions, from the country level to the world as a whole, while formally accounting for the international dependence of supply responses in different countries linked together by international trade. The measure of technological progress is the annual growth rates in total factor productivity (TFP) estimated by Fuglie (2012) for decennial periods during 1961-2010. Despite various potential weaknesses regarding number index bias and other measurement issues (Alston and Pardey, 2014), these data have the virtue of being comparable across a large number of countries.

The current article makes three contributions to the literature. First, it develops a conceptual framework that links a country's optimal demand for land to changes in domestic TFP as well as to foreign TFP growth. In the tradition of leading models of applied international trade (e.g., Anderson and Van Wincoop, 2003), the conceptual framework is rooted in Armington (1969)'s proposition that trade can be modeled by differentiating products by country of origin. As is the custom in this literature, this article relies on the tractability of the constant elasticity of substitution (CES) functional forms on both the demand and supply side of the model (e.g., Eaton and Kortum, 2002; Redding and Venables, 2004). A key implication of the model is that, for a given trade elasticity, a competition index summarizing the degree to which agricultural producers in any country are exposed to international competition is a sufficient statistic to use in inferring whether TFP growth is likely to be save or expand croplands.

The model is linearized (relative changes in all the variables), so the theory-derived reduced form seamlessly maps onto an estimable linear regression in which the marginal effects are elasticities. The derived elasticities of cropland with respect to TFP growth are conditional on the degree of exposure of national producers to foreign competitors. Therefore, the heterogeneity of the cropland elasticities with respect to TFP across countries can be fully recovered, even as the marginal effect of TFP on cropland is assumed to be homogeneous across the countries in the estimating sample. Formulas to aggregate the country level elasticities to different geographic scales are also derived, which allows for quantifying the effects of TFP growth on cropland from the country level to the world as a whole.

As a second contribution, this article finds that under current levels of international trade, only in few countries in developing Asia and sub-Saharan Africa does domestic TFP growth have a statistically significant land saving effect at national scale. This results from the fact that these countries are relatively insulated from world markets, so the elasticity of demand faced by their producers is less than one. For the overwhelming majority of countries in the sample, domestic TFP growth is either uncorrelated with changes in cropland or associated with cropland expansion. Yet, the elasticity of global cropland to a uniform change in global TFP is negative and is precisely estimated with a point estimate close to -0.35 and with a 95% confidence interval (CI) bound between -0.61 and -0.08. The differences in signs between country-level and global elasticities are reconciled through the fact that the increase in supply stemming from the combined effects of TFP growth and land expansion results in lower priced agricultural goods, which leads to supply and area reductions in other countries, partially offsetting the cropland expansion in the innovating region. When TFP growth is geographically broad, the net result is global land savings.

The third contribution of this article is to clarify the role of technology in global land use change in the context of two questions relevant for policy formulation. First, simple regression counterfactuals are used to explore the extent to which TFP growth counteracted the effects of demand growth on cropland expansion from 1991 to 2010. The counterfactual estimates suggest that the pattern of observed TFP growth in this time period offset much of the hypothetical cropland expansion that would have occurred in the absence of TFP growth. This is a noteworthy result as it is generally perceived that technological progress plays a minor role in counteracting cropland expansion due to demand growth (Rudel et al., 2009;

Byerlee, Stevenson, and Villoria, 2014). In terms of policy implications, this suggests that continued investment in agricultural R&D is a sound strategy for slowing down deforestation rates in the presence of increasing demand for agricultural goods.

The second question with relevance for policy formulation is related to the effects of regional initiatives aimed to boost productivity in some regions of the world. For investigating this question, the elasticities are aggregated by regions to examine the intra and extra-regional land consequences of targeted TFP growth in the remaining land-abundant and agriculturally suitable regions of the world. The estimates suggest that technological progress in developing Asia and sub-Saharan Africa would reduce cropland within these regions as well as in the rest of the world. In contrast, TFP growth in South America is likely to result in expansions in regional cropland, but the net global effect is to reduce global croplands. From a policy view point, this finding suggests that, in the short term, large increases in technology in Africa and developing Asia could have, beyond food security, environmental payoffs. Yet as these regions become more integrated into the world economy, as is the case of South America, such benefits, especially those associated with reduced local deforestation, are likely to dissipate.

The rest of the article is organized as follows. Section 2 briefly discusses the place of this research in the broader literature. Section 3 develops the theoretical framework used to guide the estimation below. Section 4 discusses the mapping of the theory-derived reduced form onto a linear regression; section 5 explains how the estimates of the linear regression are used to estimate various elasticities of cropland with respect to TFP growth. Section 6 explains data sources and limitations. Section 7 discusses the results, while counterfactual simulations are discussed in section 8. Some concluding remarks are given in section 9.

# 2 Related Literature: R&D Spillovers and Deforestation Leakage

Although the empirical evidence on the effects of TFP growth on cropland use across countries is thin, and practically nonexistent when the issue of international TFP spillovers is considered, there is a rich literature concerned with the international transmission of R&D investments that ultimately reflects on international TFP growth (Coe and Helpman, 1995; Fracasso and Vittucci Marzetti, 2015; Ertur and Musolesi, 2016). The main lesson from this literature is that national investments in R&D benefit other nations(Coe and Helpman, 1995; Coe, Helpman, and Hoffmaister, 2009). As in this article, the main mechanism of R&D transmission in the literature is international trade(Coe and Helpman, 1995; Coe, Helpman, and Hoffmaister, 2009). The international benefits of R&D in agriculture are also recognized, although most of the evidence is either ex-ante using simulation models, or focused in the U.S (Alston, 2002). This article is related to this literature insofar provides an environmental measure of R&D spillovers, with a focus on agriculture.

The issue of potential offset of deforestation across countries by changes in geographic production patterns also appears in many bodies of research. For instance, in the context of carbon-reduction policies, the displacement of emissions of greenhouse gases (GHG) as production moves from regulated to non-regulated areas is known as *leakage* (Karp, 2011). Leakage also means the market-mediated mechanisms that may eliminate the benefits of localized forest conservation initiatives by the displacement of production to other locations (Alix-Garcia and Wolff, 2014; Delacote, Robinson, and Roussel, 2016). Leakage is closely related to the so-called indirect land use effects of biofuels whereby higher prices associated with increased demand for biofuel crops would lead to the expansion of cropland in other regions, which in turn lead to increased emissions from deforestation. So the benefits of carbon sequestered in the biofuels feedstock are negated (Searchinger et al., 2008; Andrade de Sá, di Falco, and Palmer, 2013). A crucial distinction between biofuel or conservation policies and technological progress, is that, by definition, technological progress increases the supply of agricultural goods, while conservation measures may or may not stimulate agricultural intensification (Ollivier, 2012). Increased regional supply leads to regional lower prices (relative to other regions) which— regardless of whether localized technological progress is locally associated with cropland savings or with cropland expansion—may discourage production out of the region, thus discouraging further deforestation.

# 3 Theoretical Framework

This section derives a reduced-form demand for land relating country-level changes in cropland expansion to changes in both domestic and foreign TFP. To this end, the total demand for output in a country-level, partial equilibrium model of the aggregate agricultural sector is decomposed into bilateral demands following Armington (1969)'s model of bilateral trade, which distinguishes products by country of origin.[1]

## 3.1 Total Factor Productivity and Prices

There are $N = 1, ..., n$ producing countries selling to $M = 1, ...m$ destination markets, including domestic markets. Unless otherwise noted, producing countries are indexed by $i$ ($i \in N$) and destination markets by $j$ ($j \in M$). Aggregate agricultural production in any given country $i$ can be represented by a technology that combines land and a non-land input composite to produce an aggregate agricultural product, $Q_i$. The agricultural sector in each country operates under constant returns to scale. Therefore, dual to the production technology there is a unit cost function $C_i$ that depends on land rents, $R_i$, and the price of a non-land input composite, $W_i$. The empirical analysis relies on decennial changes in cropland and TFP; therefore, it is natural to assume a long-run equilibrium where the non-land input price is exogenous to the agricultural sector (Hertel, 1989). It is also assumed that individual producers seek to maximize profits and that this assumption carries over to

[1] In order to keep this and the next section brief, the derivation and intermediate algebraic manipulations of some key equations have been moved to the accompanying Reviewers' Appendix (RA). For ease of review and later reference, the derivations in the RA are developed step by step. Upon publication, the RA will be published on-line as Supporting On-line Materials.

the national level. Furthermore, $Z_i$ is used to denote a region-specific efficiency factor that captures TFP and thereby affects the real cost of production. Under these assumptions, the price $P$ of agricultural output produced by country $i$ and delivered to destination market $j$ can be written as:

$$P_{ij} = \frac{C_i(R_i, W_i)}{Z_i} T_{ij}, \tag{1}$$

where $T_{ij}$ are the iceberg trade costs of shipping one unit of agricultural output from origin $i$ to destination.

As a proxy for the unobservable TFP shifter $Z_i$ in (1), we will use the TFP indexes estimated by Fuglie (2012). Since the data on TFP is available in terms of growth rates, it is convenient to express the relationships in this section in terms of relative changes as they naturally bridge the conceptual and empirical frameworks. In order to distinguish the variables in levels from the variables in relative changes, we use lowercase for the latter. For instance, $z_i = dZ_i/Z_i$ is the relative change in the TFP of the agricultural sector in country $i$. Totally differentiating the price in (1) obtains the relative change in the price charged by suppliers in country $i$ in any market $j$:

$$p_{ij} = (1 - \lambda_i)r_i + \lambda_i w_i - z_i + t_{ij}, \tag{2}$$

where $\lambda_i$ 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, and $t_{ij}$ is the relative change in bilateral trade costs.

Notice that (2) is independent of the assumed functional form of the production function and simply states that, under profit maximization and constant returns to scale, the aggregate agricultural sector earns zero profits as any change in supply prices must be exhausted by changes in input prices weighted by their corresponding cost share. Equation 2 also shows that increases in TFP reduce supply prices across all the potential destination markets $j \in M$; meanwhile, changes in trade costs are bilateral and only affect the price of the good produced by country $i$ in a particular destination market $j$. Therefore, regardless of the destination market, the supply price of the agricultural good in country $i$ is given by:

$$p_i = (1 - \lambda_i)r_i + \lambda_i w_i - z_i. \tag{3}$$

## 3.2 Demand for Agricultural Output

The starting assumption is that consumers maximize a sub-utility function over agricultural products that is separable from the demand for other goods. Furthermore, this sub-utility function has a Constant Elasticity of Substitution (CES) functional form defined over all the potential sources of agricultural products, either domestic or foreign. Maximization of this sub-utility function subject to a budget constraint yields bilateral demands from agricultural products. After some manipulations, the linearized form of the CES compensated demands can be expressed as (see RA S-1.1 for the derivations):

$$q_{ij} = d_j - \sigma_i \left[ \sum_{k \neq i}^{N-1} \delta_{kj}(p_{ij} - p_{kj}) \right], \tag{4}$$

where $q_{ij}$ is the relative change in exports from country $i$ to market $j$, and $d_j$ is the relative change in demand in market $j$, also known as the expansion effect.

The second term on the right hand side of (4) is termed the substitution effect and is composed of the elasticity of substitution between domestic products and imports as well as among import sources, $\sigma_i$; the relative change in the supply price of country $i$ at the destination market $j$, $p_{ij}$, which was defined in (2); and the relative change in the supply price of a country $k$ competing with $i$ at the destination market $j$, denoted by $p_{kj}$. The terms $\delta_{ij} = P_{ij}Q_{ij}(E_j \sum_i Q_{ij})^{-1}$ are the *budget shares* defined as country $j$'s share of its import budget spent on products from supplier $i$.

The substitution effect is useful to understand how any two exporters affect each other as they compete in different markets. For instance, if the price charged by country $i$ increases while domestic demand and the prices charged by the other suppliers of country $j$ remain constant (i.e., $d_j = 0$, and $p_{kj} = 0$ for any country $k \neq i$), country $j$ would reduce its demand from country $i$ in direct proportion to $\sigma_i$, but in indirect proportion to the budget shares $\delta_{ij}$.

The next step is to aggregate the changes in bilateral demands to the change in overall demand facing country $i$. Before doing so, recall that the changes in trade costs $t_{ij}$ are the only element linking changes in supply prices in one country to the sales prices prevailing in different destinations (2). For our purposes, these changes in trade costs can be ignored (i.e., $t_{ij} = 0$), so the simpler price expression in (3) can be used. With this simplification in mind, summing the $m$ bilateral equations (4) and rearranging terms yields the total demand for agricultural products facing producers in country $i$ as a function of income in all the markets to which country $i$ sells agricultural products, as well as of the supply prices charged by all the suppliers that compete with country $i$ in those markets (see RA S-1.2 for the derivations):

$$q_i^D = \sum_j^m \gamma_{ij} d_j - \sigma_i \left[ \sum_{k \neq i}^{n-i} \sum_j^m \gamma_{ij} \delta_{kj} \left( p_i - p_k \right) \right], i \in j. \tag{5}$$

In line with the previous discussion, the first and second terms on the right hand side of (5) are the overall expansion and overall substitution effects. Equation (5) also introduces a new term, $\gamma_{ij}$, which is a *revenue share* calculated as $\gamma_{ij} = P_{ij}Q_{ij}(P_i \sum_j Q_{ij})^{-1}$; in other words, the revenue share is defined as the share of total revenues in country $i$ that are obtained from the sales in market $j$. In the overall expansion effect of (5) the revenue shares weight the importance of income changes in each of the individual markets $j$ served by $i$. In the overall substitution effect, the revenue shares also weight the contribution of the substitution effects in individual markets by relatives changes in those markets' demands.

### 3.2.1 Competition in International Markets

Equation (5) shows that the change in the demand for country $i$'s products depends on both the market share of its competitors in the destination market ($\delta_{kj}$) and on the importance that the destination market has for $i$'s total sales of agricultural products ($\gamma_{ij}$). Indeed, the sum of the products of the budget and revenue shares within the overall substitution effect in (5) is a key piece of information in our analysis. Because of this, it is convenient to map this sum onto a new variable, $\omega_{ik} = \sum_j^m \gamma_{ij}\delta_{kj}$, which is a *bilateral competition index* between countries $i$ and $k$ in each $j \in m$ market, including $i$'s own market and the market of its competitor $k$ (i.e., $i, k \in M$ as well).

There are a few properties worth noting about the bilateral competition indexes. First, they are not symmetric (i.e., $\omega_{ik} \neq \omega_{ki}$); therefore, their interpretation is directional. By convention, the first subindex refers to the exporter of interest, while the second index denotes a competitor. As a preview of the discussion below, among the largest competition indexes in the data is that between Mexico and the U.S., $\omega_{MEX,USA} = 0.34$; however, the bilateral competition index between the U.S. and Mexico is much lower, $\omega_{USA,MEX} = 0.06$. These indexes suggest that Mexico generates an important part of its agricultural revenues in markets in which the U.S. has a non-trivial market share; in contrast, most U.S. sales of agricultural products are in markets in which Mexico has a relatively low market share. An important feature of these indexes is that the domestic markets are part of the index. Indeed, 47% of the bilateral competition index between Mexico and the U.S. is explained by the competition of Mexico's producers with U.S producers in Mexico's markets.

Second, by construction, the bilateral competition indexes range from zero to less than one. There are two extreme situations which give rise to zero-valued bilateral competition indexes with *all* the potential set of competing countries. One extreme would be a country operating in autarky. Under autarky, the share of the domestic markets in total sales is one, i.e., $\gamma_{ii} = 1$, while the budget shares allocated to potential competitors are zero, i.e., $\delta_{ki} = 0$ for all countries $k \neq i$. The other extreme situation is for a country that does not produce agricultural products and therefore earns no agricultural revenues in any market. In general, most countries display some zero-valued bilateral competition indexes because neither the exporting country nor the competitor sell in the same markets.

Regarding the upper bound of the bilateral competition indexes, a value near one with a specific competitor $k$ would arise if a country sells all its agricultural products in the domestic market $\gamma_{ii} = 1$, but such sales satisfy only a marginal share of total demand, and the excess demand is supplied by only one country, such that $\delta_{ki} \to 1$. These extreme cases serve to increase the understanding of the bilateral competition indexes but they are not found in the actual data. In reality, most of the countries in the sample used for the empirical work below produce agricultural goods and engage in exports and imports with more than one country. In terms of notation, it is useful to replace the innermost summation of the products $\gamma_{ij}\delta_{kj}$ of (5) with $\omega_{ik}$ to get a more compact form of the total demand facing producers in country $i$:

$$q_i^D = \sum_j^M \gamma_{ij} d_j - \sigma_i \left[ \sum_{k \neq i}^{N-1} \omega_{ik} \left( p_i - p_k \right) \right], i \in j. \tag{6}$$

### 3.2.2 The Own Price Demand Elasticities of Domestic and Total Consumption

In closing the discussion about the demand side of the model, it is useful to consider the role of budget and revenue shares in the own-price elasticity of demand faced by producers in country $i$. A well known property of the CES bilateral system is that the own price elasticity of demand for domestic consumption in country $i$, $q_{ii}$, is given by $\eta_{ii} = q_{ii}/p_i = -\sigma_i(1-\delta_{ii})$, which implies that for countries in which domestic purchases represent a small share of their total expenditures, the absolute value of $\eta_{ii}$ is close to the elasticity of substitution $\sigma_i$ (Armington, 1969).

Broadening the scope to include both domestic and foreign demand for the domestically produced good, as in (6), yields the own price elasticity of total demand as $\eta_i^D = q_i^D/p_i = -\sigma_i \sum_{k\neq i}^{N-1} \omega_{ik}$. The term $\sum_{k\neq i}^{N-1} \omega_{ik}$ is a an *aggregate competition index* measuring the extent of aggregate exposure to foreign competitors in foreign markets (note that the domestic market $i$ is excluded form the sum); therefore, the total demand elasticity facing producers in country $i$ will converge to $\sigma_i$ the larger the producers' exposure to competition with producers in international markets.

The aggregate competition indexes play a prominent role in the derivation of the cropland elasticities with respect to domestic and foreign TFP as discussed below. Therefore, the cost of introducing yet another notation symbol will be more than compensated for by the convenience of being able to simply refer to the aggregate competition index of country $i$ as:

$$\Omega_i = \sum_{k\neq i}^{N-1} \omega_{ik}. \tag{7}$$

So, for instance, the own price elasticity of total demand is $\eta_i^D = -\sigma_i\Omega_i$.

### 3.3 Land and Product Market Equilibrium

The next step in obtaining a reduced form expression relating changes in cropland to changes in TFP is to link the demand for land to the bilateral demands for agricultural output. Analogously to the demand side, we assume that the underlying production technology can be parsimoniously represented by a CES production function that combines land and a non-land input composite to produce a unit of agricultural output. The relative change in the CES derived demand for land in country $i$, derived in the RA S-1.3, is given by:

$$l_i^D = (q_i^S - z_i) - \phi_i\lambda_i (r_i - w_i). \tag{8}$$

In this equation, the first right hand side term $q_i^S - z_i$ is the expansion effect, given by the relative change in overall demand for agricultural products net of changes in productivity. Note that this equation reflects the fact that technological progress ($z_i$) counteracts the expansion effect stemming from changes in overall demand for agricultural products, $q_i^S$. That is, keeping prices constant, for a given increase in demand for agricultural products, an increase in TFP reduces the demand for land. The second term is the substitution effect, which depends on the change in land rents ($r_i$) relative to changes in the price of the non-land input. Lastly, $\phi_i$ is the elasticity of substitution between land and non-land inputs.

The land supply is given by $l_i^S = \nu_i r_i$ where $\nu_i$ is the land supply elasticity (Hertel, 1989). In the competitive equilibrium, $l_i^S = l_i^D$. From this equilibrium condition, we solve for $r_i$ to obtain the equilibrium land rents: $r_i^* = (q_i - z_i + \lambda_i\phi_i w_i)(\nu_i + \lambda_i\phi_i)^{-1}$. These land rents can in turn be used to eliminate $r$ in (8), to then solve for $q_i^S$, thus obtaining the equilibrium supply of agricultural output :

$$q_i^S = l_i^* \frac{\nu_i + \phi_i \lambda_i}{\nu_i} + z_i - \phi_i \lambda_i w_i. \tag{9}$$

The land supply in (9) depends solely on supply factors: non-land input costs shares, land supply and input substitution elasticities, and changes in input prices and TFP. In contrast, the demand for agricultural output in (6) depends on both income and supply prices in country $i$ as well as in the other countries linked to $i$ through international trade. The connections among land demand, income, and foreign prices are made by using the fact that in equilibrium, for any country $i$, $q_i^S = q_i^D$, which entails equating (6) to (9). From the resulting equilibrium, we can solve for the optimal land allocation that satisfies the market equilibrium to obtain:

$$\begin{aligned} l_i^* = \Bigg[ & \lambda_i \phi_i w_i - z_i + \sum_j^M \gamma_{ij} d_j \\ & - \sigma_i \left( \sum_{k \neq i}^{N-1} \omega_{ik} (z_k - z_i) + \lambda_i \sum_{k \neq i}^{N-1} \omega_{ik} (w_i - w_k) + (1 - \lambda_i) \sum_{k \neq i}^{N-1} \omega_{ik} (r_i - r_k) \right) \Bigg] H_i \end{aligned} \tag{10}$$

where $H_i = \nu_i (\nu_i + \lambda_i \phi_i)^{-1}$ (detailed derivations are in the RA S-1.4).

## 3.4 TFP Growth and the Equilibrium Demand for Land

Equation 10 provides useful insights into the question of whether TFP growth in a given country reduces or increases the country's cropland extent. Because (10) is an equilibrium equation with all the variables transformed to relative changes (i.e., $z_i = dZ_i/Z_i$), comparative statics of the changes in TFP on the equilibrium demand for land are relatively straightforward. The analysis is further facilitated by the fact that $H_i$, $\phi_i$ and $\sigma_i$ are all positive. It is also helpful to use (7) to simplify (10) in terms of the elasticity of total demand:

$$\begin{aligned} l_i^* = \Bigg[ & \lambda_i \phi_i w_i - z_i + \sum_j^M \gamma_{ij} d_j \\ & + |\eta_i^D| [z_i - \lambda_i w_i - (1 - \lambda_i) r_i] - \sigma_i \left( \sum_{k \neq i}^{N-1} \omega_{ik} z_k - \lambda_i \sum_{k \neq i}^{N-1} \omega_{ik} w_k - (1 - \lambda_i) \sum_{k \neq i}^{N-1} \omega_{ik} r_k \right) \Bigg] H_i. \end{aligned} \tag{11}$$

In contrast to the derived demand for land (8), in (11), domestic TFP growth does not unambiguously reduce the demand for land. Rather, for any country $i$, the elasticity of cropland with respect to TFP is:

$$l_i^* (z_i)^{-1} = H_i \left( |\eta_i^D| - 1 \right), \tag{12}$$

which indicates that TFP growth will increase the demand for land if the absolute value of the elasticity of total demand is greater than one. In what follows, (12) is referred to as the cropland elasticity with respect to changes in *domestic* TFP, or domestic cropland elasticity for short. Another objective of this article is to explore the extent to which TFP growth spillovers result in changes in land use elsewhere. Equation 10 indicates that 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, formally, $l_i^*(z_k)^{-1} = -H_i\sigma_i\omega_{ik}$. Throughout the rest of the article, this elasticity is referred to as the *bilateral* cropland elasticity.

The effects of TFP growth at home and abroad on the domestic demand for land are the focus of this article; however, understanding the effects of the other variables in equations 10-11 will prove helpful in interpreting the regression results presented below. As stated in the context of (8), land and non-land inputs are assumed to be substitutes in production. Yet, as in the case of TFP growth, in equilibrium, the effect of an increase in the price of the non-land input on the demand for the land input also depends on the elasticity of total demand(see e.g., Chavas and Helmberger, 1996, p. 113-115). Using (10) yields the elasticity of demand for land with respect to changes in non-land input prices as:

$$l_i^*(w_i)^{-1} = \left[\phi_i - |\eta_i^D|\right] \lambda_i H_i, \tag{13}$$

so if the absolute value of the elasticity of total demand is larger than the elasticity of input substitution $\phi_i$, a reduction in non-land input prices will increase the demand for land, even though land and non-land inputs are substitutes.

Turning abroad, an increase in the price of the non-land input in a foreign country will increase the demand for land in country $i$, suggesting that foreign non-land inputs and the domestic land input are substitutes. (The effect is proportional to the elasticity of substitution $\sigma_i$, weighted by the domestic cost-share of non-land inputs as well as the bilateral competition index, and the term $H_i$ i.e. $l_i^*(w_k)^{-1} = H_i\sigma_i\lambda_i\omega_{ik}$.)

The signs of the effects of the other two variables, demand and land rents, are more straightforward. For instance, increases in overall demand in any destination market will increase the demand for land in direct proportion to the revenue shares coming from that market, formally, $l_i^*(d_j)^{-1} = H_i\gamma_{ij}$. Finally, in (10), if land rents in country $i$ grow faster than land rents in a competitor country $k$ so that $r_i > r_k$, country $k$ gains a cost advantage in production, thus displacing country $i$ from some of the destination markets $M$. As a consequence, the demand for land in country $i$ falls. The net effect is a function of the elasticity of substitution $\sigma_i$, the importance of land in total costs $(1-\lambda)$, and the bilateral competition index that connects producers of both countries in different destination markets .

# 4 Empirical Strategy

Equation 10 is a reduced-form, equilibrium, land demand equation estimable with historical data. To convert (10) into an estimable equation, add an error term $v_{it}$ whose properties are discussed below; group together the parameters $\sigma_i$, $\lambda_i$, $\phi_i$, and $\nu_i$; finally, add a time subscript $t = 1, ..., T$ as the regression will be estimated using a panel of countries observed over time. The regression counterpart to (10) is given by:

$$
\begin{aligned}
l^*_{it} = \beta_1 z_{it} + \beta_2 \sum_{k}^{m} \omega_{ikt}(z_{kt} - z_{it}) + \beta_3 w_{it} + \beta_4 \sum_{kt}^{m} \omega_{ikt}(r_{it} - r_{kt}) \\
+ \beta_5 \sum_{kt}^{m} \omega_{ikt}(w_{it} - w_{kt}) + \beta_6 \sum_{j}^{n} \gamma_{ijt} d_{jt} + \beta_7 \bar{L}_i + \mu_i + \varepsilon_{it}..
\end{aligned}
\tag{14}
$$

where $\beta_1 = -H$, $\beta_2 = -H\sigma$, $\beta_3 = H\lambda\phi$, $\beta_4 = -H\sigma(1-\lambda)$, $\beta_5 = -H\sigma\lambda$ and $\beta_6 = H$. The signs on the right hand side in each of these coefficients provide the expected signs of the empirical estimates. Also, note that whereas the parameters $\lambda$, $\phi$, $\nu$, and $\sigma$ were indexed by country in the preceding discussion, the regression restricts them to being constant across countries.

The main identifying assumption of the effect of TFP on cropland expansion is that changes in current TFP are the inertial consequence of investments in agricultural R&D one or more decades ago (Fuglie, 2012; Wang et al., 2013) and therefore, TFP and cropland growth are not simultaneously determined. A main lesson from the literature on R&D spillovers is that an important part of a country's TFP may be the consequence of TFP growth spillovers coming from other countries (Coe and Helpman, 1995; Alston, 2002; Coe, Helpman, and Hoffmaister, 2009). The inclusion of changes in TFP growth in all the other countries (weighted by the bilateral competition indexes) along domestic TFP directly controls for the correlation between TFP growth among countries. In addition to the exogeneity of current TFP to current decisions about land use, including contemporaneous estimates of land rents and input prices, helps to further reduce potential biases in the parameter estimates stemming from interactions between TFP growth and changes in agricultural returns.

The regressions are estimated using pooled time series of country-level data from 1991 to 2010 and including seventy countries. The panel data structure allows controlling for time-invariant, country-specific factors that can further contaminate the estimated relationship between TFP growth and cropland expansion. Therefore, the model is estimated using country and fixed effects, so that $\upsilon_{it} = \mu_i + \varepsilon_{it}$, where $\mu_i$ are country intercepts and $\varepsilon_{it}$ are the regression errors which are assumed to be uncorrelated with the regressors.

Another potential source of endogeneity are the physical possibilities of land expansion in each country in the sample. The theory of induced innovation suggests that land-constrained countries would achieve greater rates of output growth by adoption of land-saving technologies (Hayami and Ruttan, 1970). Such technologies may not affect TFP growth, however, Lusigi and Thirtle (1997) show that TFP growth in African agriculture is positively correlated with labor/land ratios in the sense that the more land-constrained countries (as measured by labor/land ratios) tend to show higher rates of TFP growth. To the extent that relative land abundance may influence the diffusion of new technologies, causality might run backward to the proposed identification strategy because countries with little room for expanding their cropland may invest more in R&D and technology adoption activities conducive to higher TFP growth than land-abundant countries where there are fewer incentives to increase land productivity. In order to control for the effects of constraints to cropland expansion on TFP, a variable that controls for the share of cropland in the total amount of land suitable for agricultural expansion at the beginning of each decade ($\bar{L}_i$), is included (and discussed in the data section below).

# 5 Elasticities of Cropland with Respect to TFP

Table 1 displays formulas for elasticities ranging from national to global scales (detailed derivations of these expressions are in the RA S-1.5). The domestic and bilateral cropland elasticities derived from (11) are summarized in the two first rows of table 1 (column labeled "Structural Parameters"). The corresponding formulas as functions of the parameter estimates of (14) are under the column labeled "Regression Parameters".

For any single country, there could be up to $N$ non-zero bilateral elasticities which are difficult to summarize. A more manageable measure is the *foreign* cropland elasticity, which is the share-weighted sum of bilateral elasticities using as weights the shares of global cropland accruing to each country $k$, denoted by $\theta_k$ in table 1. This elasticity, shown in the third row of table 1, measures the aggregate effect of TFP growth in any country on the rest of the world, and is therefore an aggregate measure of TFP spillovers. Moreover, using the cropland shares to weight the own and foreign cropland elasticities yields the *total* cropland elasticity, which combines in a single measure the global cropland effects of TFP growth in a given country $i$ (fourth row of table 1).

In many instances, the interest is on the direct and indirect land use effects of regional changes in TFP; for instance Villoria et al. (2013) analyze the spillover effects of increasing yields of oil palms in Indonesia and Malaysia, and Hertel, Ramankutty, and Baldos (2014) investigate the regional and global consequences of increasing TFP growth in sub-Saharan Africa. As shown in the fifth row of table 1, using cropland shares allows for aggregating the own and foreign elasticities of each country within an innovating region, denoted by $O$. This *regional* elasticity is interpreted as the change in regional cropland, given a 1% increase uniformly distributed across the countries that form the region. A formula for the *extra-regional* elasticity, which captures the spillover effects of regional innovation into a different region of interest denoted by $D$, is provided in the sixth row of table 1.

Finally, the last row of table 1 shows the *global* cropland elasticity, which is defined as the changes in global cropland that would result from a one percent increase in TFP in each country in the world. This is an interesting result that allows for assessing the effects of global, broad-based, and uniformly distributed technological change, net of market-mediated, spillover effects. In closing, note that all the elasticities discussed here are functions of cropland shares and competition indexes, both treated as constants, and of the estimates of the regression parameters $\beta_1$ and $\beta_2$. This allows for straightforward calculation of standard errors of the different estimated elasticities, a task that will be accomplished using the delta method (Greene, 2008, p. 1055).

# 6 Data

Equation 14 is estimated using a two-period panel ($t$ = 1991-2000 and 2001-2010) covering seventy countries (listed in Appendix). These countries represent 74% of worldwide cropland, and they account for 91% of global production, 86% of global imports, and 91% of global exports. The focus on 1991-2000 and 2001-2010 is partially dictated by data availability. The year 1990 represents a major break in the available time series of the data on production, consumption and trade due to the appearance of new countries after the dissolution of the Soviet Union, the split-up of Yugoslavia, and the separation of Eritrea from Ethiopia. Aggregating these countries back into their former political unions in order to obtain longer time series greatly reduces the resolution of the data, particularly in GDP and bilateral trade flows.

More importantly, prior to the 1990s, international markets for agricultural products were extremely thin and unstable. Domestic and trade policies in the major agricultural producing countries of the world were aimed at isolating their domestic markets from world market instability (Johnson, 1975, 1987). It was not until the mid 1990s, following the signature of the WTO Agreement on Agriculture, that global agricultural trade started to develop (Martin and Winters, 1995). The second half of the 1990s marks a fundamental change in the configuration of world agricultural markets in terms of traded volumes as well as in both the number of countries involved and the products being traded (Anderson, 2010). As the intensity of competition among countries depends on both the size of the trade flows and the number countries served by each exporter, the period after 1990 offers a more robust basis for identifying the effects of competition on land use changes.

Summary statistics for the variables used in the regression are in table 2. With the exception of the shares at the bottom of table 2, all the variables are average annual growth rates from 1991 to 2000 and from 2001 to 2010 (see note to table 2 for details). Using annual growth rates over decades facilitates comparisons with the agricultural TFP indexes from Fuglie (2012), described just below, and allows for direct interpretation of the parameter estimates as elasticities. The robustness of the results to alternative transformations capturing decennial changes are discussed in RA S-2.

## 6.1 Cropland and TFP

The dependent variable, $l_{it}$, is the decade-specific average annual growth rates in country-level cropland. Cropland is defined as the sum of arable land and permanent crops both available from FAOSTAT (FAO, 2016).

The measures of TFP growth ($z_{it}$) come from Fuglie (2012) who estimated average annual growth rates of agricultural TFP over 10-year periods from 1961 to 2009, and from Fuglie (2017) who provides updates to 2010 and beyond. TFP is estimated as the difference between production and input use growth rates using FAOSTAT and other sources (Fuglie, 2012). These estimates of TFP have been criticized due to the likely bias arising from errors in measuring capital and material inputs (see Alston and Pardey, 2014, for an extensive discussion). These indexes may also suffer from index number biases associated with the use of relatively constant cost structures over time. The biases arise because constant cost structures may mask input substitution due to changing relative prices (Fuglie, 2012). But despite the weaknesses of the TFP indexes, and in the absence of better data, they remain the only source of publicly available, globally comparable changes in agricultural total factor productivity patterns across countries.

## 6.2 Market Shares and Competition Indexes

The next variable in (14) is the competition-index-weighted sum of the relative change in TFP growth of a given country relative to its trading partners, i.e., $z_{it} - z_{kt}$, using as weights the bilateral competition indexes $\omega_{ikt}$. In turn, the competition indexes are the product of the budget and revenue shares, $\delta_{ijt}$ and $\gamma_{ijt}$ from the linearization of the CES bilateral demand functions (4) and their aggregation across destinations (5). In practice, the budget and revenue shares are calculated using the following expressions (time subscripts are omitted for clarity):

$$\begin{aligned} \delta_{ij} &= P_{ij}Q_{ij}(E_j \sum_i Q_{ij})^{-1}, \\ \gamma_{kj} &= P_{ij}Q_{ij}(P_i \sum_j Q_{ij})^{-1}, \\ \sum_j \delta_{ij} &= \sum_i \gamma_{ij} = 1. \end{aligned} \tag{15}$$

The denominator in the budget shares is total consumption of agricultural goods in country $i$ valued using the CES price index ($E_i$) of the underlying utility function. As a proxy of total consumption, the value of net agricultural exports is subtracted from the gross value of agricultural production, both from FAOSTAT. The denominator in the budget shares is total agricultural production valued at domestic prices, $P_i$, which is proxied by FAOSTAT's gross production values.

The numerators of both budget and revenue shares are source-specific purchases of agricultural goods. They include domestic purchases or sales (i.e., $P_{ii}Q_{ii}$) and also the value of import and export transactions with various foreign countries (i.e., $P_{ij}Q_{ij}$ for $i \neq j$ is the value of exports from country $i$ to country $j$). Domestic purchases $P_{ii}Q_{ii}$ are calculated as the difference between the gross value of agricultural production and the value of total agricultural exports, both from FAOSTAT.

Bilateral trade in the FAOSTAT database is not available in value terms. The value of bilateral flows is readily available from Gehlhar (2012, GTAP database) and other sources based on UN-COMTRADE. In most cases, UN-COMTRADE's bilateral trade values do not add up to FAOSTAT's total trade values. Because FAOSTAT total export values were used to calculate both total consumption in the denominator of the budget shares and domestic sales for the numerators of both budget and revenue shares, any discrepancy in the total trade values violates the condition that the shares add to one in (15). As an alternative, FAOSTAT's total trade values were shared-out using bilateral trade value shares from Gehlhar (2012), aggregated over all the food sectors in the GTAP classification (listed in Appendix); this procedure preserves the observed pattern of bilateral trade flows while matching FAOSTAT aggregate trade values.

The budget and revenue shares are calculated using total decennial values. This avoids the extreme sensitivity of annual swings in production and trade while reflecting the geographic pattern of trade in the decennial scale used to estimate the parameters of (14). As shown at the bottom of table 2, the domestic shares are negatively skewed: Only a quarter of the countries in the sample have domestic revenue shares of less than 46% while for half of the countries, domestic revenue shares are greater than 74%. Likewise, only a quarter of the countries in the sample have domestic budget shares of less than 51% while for half of the countries, domestic budget shares are greater than 76%. This implies that domestic purchases and revenues tend to dominate the total sales and consumption.

The bilateral competition indexes $\omega$ are the product of the budget and revenue shares. Table 3 shows the country pairs with the ten largest bilateral competition indexes. In five of these cases, the largest competition index is with the U.S. The other four cases involve countries with large agricultural sectors, such as France, Italy, Spain, and Portugal. The interpretation of these indexes is that Canada, Mexico, Costa Rica, Panama, and Honduras face intense competition from the U.S.; the Netherlands faces intense competition from France, Italy, and Spain; and Namibia faces intense competition from South Africa. The converse — as shown by the reciprocal bilateral competition indexes in the last column of table 3 — of course, is not necessarily true. The bilateral competition indexes are used to weight the relative differences in TFP growth, non-land input prices, and land rents.

### 6.3 Input Prices, Demand, and Cropland Shares

The next variables in (14) are decennial changes in land rents and non-land input prices, $r_{it}$ and $w_{it}$, used to estimate parameters $\beta_3$-$\beta_5$. Land rents and non-land input prices are mostly unavailable at the country level. In their absence, implicit fertilizer prices (as a proxy for non-land input prices) and land rents are derived as the portions of total costs of agricultural production (in constant 2004 US$) accruing to fertilizer and land (see Appendix for details). Per capita gross domestic product (GDP) is the ratio of constant GDP to population counts, both from The World Bank (2017). The cropland shares $\bar{L}_i$ in (14) are 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) (details in Appendix).

## 7 Results and Discussion

Table 4 displays parameter estimates for several specifications using the variables described in the Data section. The preferred specification formulated in (14) is displayed in column 1. The results in the other columns explore alternative specifications, which will be discussed toward the end of the section. At a glance, all the parameter estimates have the expected signs, are of comparable magnitudes across specifications, and are statistically significant at least at a 90% confidence level.

## 7.1 Cropland Elasticities

As discussed above, $\beta_1$ has a direct interpretation as the global elasticity of cropland following a 1% increase in TFP uniformly distributed across the world. The point estimate for this elasticity is -0.348 (column 1 in table 4; 95% CI bound by -0.61 and -0.08). As an illustrative counterfactual, if annual TFP growth rates in each country in the sample would match the global average observed from 2001 to 2010 (1.82%), the global cropland would decline by a point estimate of 6.12%, or 69.75 million hectares (Mha), with a 95% CI between 18.22 and 121.60 Mha. To put these results in perspective, consider that in 2010, Indonesia, a major hot spot of deforestation, had 47.3 Mha under primary forests[2]; while Brazil, which hosts two thirds of the Amazon forest, had nearly 477 Mha under primary forests[3].

In a focus on individual countries, the size of the domestic cropland elasticity with respect to TFP growth is $-0.348 + 1.402\Omega_i$, where, to reiterate, $\Omega_i$ captures the exposure of the producers in country $i$ to international competition (7). In light of (12), the ratio $\beta_1/\beta_2$ indicates that $\Omega_i \approx 0.25$ (95% CI: 0.11-0.38), which is the threshold that separates countries facing a price-inelastic from a price-elastic total demand. Similarly, $\Omega_i \approx 0.25$ is the threshold that separates countries in which domestic TFP growth is cropland saving from those in which TFP growth is associated with cropland expansion.

The upper panels of figures 1 and 2 display 95% CI for the domestic cropland elasticities for each country and decade in the sample. Three patterns in figures 1 and 2 deserve special mention. First, it is only in a handful of countries—Nigeria in Africa; and China, India, and Nepal in Asia—that growth in domestic TFP leads to cropland reductions under 2001-2010 trade patterns. Second, from 1991-2001 to 2001-2010, many countries in Africa, the Americas, and Asia transitioned from regimes in which TFP had a neutral or negative effect on cropland expansion to regimes in which domestic TFP growth actually incentivized cropland expansion. These are the cases of Namibia and Senegal in Africa; Ecuador, Mexico, Nicaragua, and Paraguay in the Americas; and Israel and Sri Lanka in Asia. Third, large exporters of commodities and other foods and beverages such as the Cote d'Ivoire in Africa; Argentina, Canada, Costa Rica, and Chile in the Americas; and Australia, Malaysia, and Thailand in Asia display relatively large, positive domestic cropland elasticities with respect to TFP. Many of the countries in Europe also display large, positive domestic cropland elasticities.

The next effect of interest is that of foreign TFP on domestic cropland, captured by the the bilateral cropland elasticities. Using the parameter estimates in column (1) of table 4, the bilateral elasticity of country $i$ is $-1.402\omega_{ki}$, where $\omega_{ki}$ are the bilateral competition indexes, which are aggregated over competing countries to get a foreign cropland elasticity (see table 1). Confidence intervals for the foreign cropland elasticities are displayed in the

[2] http://rainforests.mongabay.com/deforestation/2000/Indonesia.htm
[3] http://rainforests.mongabay.com/deforestation/2000/Brazil.htm

middle panels of figures 1 and 2. Across the board, the foreign elasticities are negative and statistically significant. The largest foreign cropland elasticity in the sample accrues to the U.S. As displayed in the middle panel labeled "Americas" in figure 1, a 1% increase in U.S. TFP reduces cropland expansion in the rest of the world by a point estimate of approximately 0.8% with a 95% CI bound by -0.11% and -0.04%. As is evident from the figure, the other countries with relatively large foreign cropland elasticities are Canada, Brazil, Argentina and Mexico.

Moving westward in figure 1, note that the largest foreign elasticities in Africa, those of Egypt and South Africa, are a fraction of those found in the Americas. This is explained by the fact that the foreign elasticities are weighted by both global cropland shares and the degree to which a country is exposed to international trade (table 1), both of which are larger in most of the countries in the Americas than in the countries in Africa. In (figure 2), China and Japan display the largest foreign cropland elasticities in Asia, yet their magnitudes are similar to those found in Africa. Finally, in Europe the largest foreign elasticities are those accruing to France, Germany, Italy, and Spain, although the magnitude of these elasticities is moderate, and is in line with countries in the Americas, except for the U.S.

The bottom panels of figures 1 and 2 show that for most countries, the negative foreign cropland elasticities compensate the land expansion effects associated with domestic cropland elasticities, yielding negative total cropland elasticities. The most notable exceptions to this pattern are Canada in Australia countries in which TFP growth is associated with both domestic and foreign land expansion.

## 7.2 Variables Other than TFP

The marginal effect of changes in domestic fertilizer prices on cropland expansion is $0.083 - 0.163\Omega_i$. In light of (13), in countries where $\Omega_i$ is lower than 0.51 (at $\Omega_i = 0.51$, $0.083 - 0.163\Omega_i \approx 0$), the marginal effect of changes in domestic fertilizer prices on cropland expansion is positive, confirming that empirically, land and non-land inputs are substitutes in production.

Turning abroad, the marginal effect of foreign fertilizer prices on domestic cropland expansion is $0.163\omega_{ik}$. Thus, a 1% increase in fertilizer prices in country $k$ that competes with $i$ in some destination markets will increase land use in country $i$, which makes foreign fertilizers and domestic cropland substitutes. The strength of the substitution effect is regulated by the bilateral competition index $\omega_{ik}$.

The coefficient $\beta_5$ measures the effects of changes in land prices in country $i$ relative to its competitors. This effect is negative, confirming the theoretical prediction that a relative appreciation of the land rents at a competitor country lead to an increase in the demand for land in country $i$.

The next coefficient, $\beta_6 = 0.211$, measures a significant and sizable positive effect of changes in revenue-share weighted GDP per capita on cropland expansion. Further insight on the effects of growth in demand are offered in column 2 of table 4 by allowing the effect to differ between domestic ($\beta_{6[D]}$) and foreign demand ($\beta_{6[F]}$): Both estimates are also precisely estimated and their sizes are of consequence. A point that is worth emphasizing is that these parameters are estimated using revenue-share weighted GDP growth rates, so for example, for a country in which 95% of total sales are destined for the domestic market, an increase in GDP of 1% would lead to an increase in cropland use of $(0.95 \times \widehat{\beta}_{6[D]} = 0.16\%)$. Assuming that the foreign revenue share is equally split across importers, in order to achieve the same level of cropland expansion with changes in foreign per capita GDP, every importer would need to grow by 4%, i.e., $(0.05 \times \widehat{\beta}_{6[F]}) \times 0.04 = 0.16\%$.

The estimate on the share of suitable land for agriculture under cropland at the beginning of each decade is negative ($\widehat{\beta}_7 = -0.072$ in column 1 of table 4), indicating that countries where most of the suitable land is already under cropland tend to have lower decennial changes in cropland. The motivation for including the cropland share is that past investments in R&D, which reflect on current TFP growth, were a response to a perceived land scarcity. To the extent that land scarcity is relatively fixed over time, this could introduce simultaneity bias between contemporaneous TFP growth and cropland changes. We investigate the support of this mechanism in the data by interacting the TFP measures with the cropland share (column 3, table 4). The interaction terms are not significant and add no additional explanatory power to a model without these interactions (formally, a Wald-test comparing the full model in column 3 with the restricted model in column 1 fails to reject the null hypothesis that the models are statistically different.)

### 7.3 Robustness to Alternative Smoothing Procedures of Decennial Endpoints

An empirical source of uncertainty is that the conversion of all time series to annual growth rates is but one of many ways to summarize decennial changes in cropland and other variables. A natural alternative is to estimate equation 14 using relative changes between the beginning and ending years of each decade. That is, for variable $Y$, the relative change between the beginning (B) and ending (F) years of a given decade is calculated as $y = (Y_F - Y_B)/Y_B = \Delta Y/Y_B$. Relative changes may be sensitive to atypically low or high values of the different variables associated with the natural fluctuations of the underlying supply and demand shifters that determine the observed variables in any given year. In order to smooth the atypical values, three alternative methods were used: three-year averages around the initial and ending years of each decade; Hodrick-Prescott filtered time series, a procedure used by Fuglie (2012) to smooth the sharp fluctuations in the time series of output value and input use that underlie the cross-country calculation of TFP; and decennial relative changes implied by the growth rates (See appendix S-3.) The results, displayed in table S-1 of the RA indicate that the results in the table 4 are robust to the alternative smoothing procedures.

# 8 Implications: Demand, Technology, and Regional Innovation

It is generally assumed that technological improvements in agriculture have not been large enough to counteract the cropland expansion caused by growing demand (e.g., Byerlee, Stevenson, and Villoria, 2014). This section uses the parameter estimates discussed above to explore this questions using in-sample predictions that isolate the effects of growth in TFP and per capita GDP as well as their interaction. The land use effects of regional initiatives to improve agricultural technology are discussed next.

## 8.1 Demand vs. Technology

The procedure is as follows. Start with the fitted values $\hat{l_{it}} = \mathbf{x_{it}'}\hat{\boldsymbol{\beta}} + \hat{\mu}_i$, where $\mathbf{x_{it}}$ and $\hat{\boldsymbol{\beta}} + \hat{\mu}_i$ are the matrix of regressors and the vector of the parameter estimates, including country fixed effects, as specified on the right hand side of (14). Then define two alternative matrices of regressors. The matrix $\mathbf{h^1_{it}}$ is a replica of $\mathbf{x_{it}}$ with all the variables that do not involve TFP growth or per capita GDP set equal to zero. The predictions using $\mathbf{h^1}$, denoted by $\hat{l_{it}}^1 = \mathbf{h^{1'}_{it}}\hat{\boldsymbol{\beta}} + \hat{\mu}_i$, isolate the combined effect of TFP and per capita GDP growth from all the other sources of variation in the regression. The second matrix, $\mathbf{h^2_{it}}$ is a replica of $\mathbf{h^1_{it}}$, in which the terms involving TFP growth ( $z_{it}$ and $\sum_k^m \omega_{ikt}(z_{kt} - z_{it})$) are also set equal to zero. Therefore, the predictions using $\mathbf{h^2}$, denoted by $\hat{l_{it}}^2 = \mathbf{h^{2'}_{it}}\hat{\boldsymbol{\beta}} + \hat{\mu}_i$, isolate the effect of per capita GDP growth on cropland growth. By summing up the changes in physical area implied by either set of predictions across countries the counterfactual values of global cropland expansion driven by changes in GDP per capita, with and without the effect of TFP growth, are obtained for the periods under study.

Both the fitted values $\hat{l_{it}}$ and the two sets of predictions $\hat{l_{it}}^1$ and $\hat{l_{it}}^2$ are predictions of the expected value of $l_{it}$ conditional on the specific values taken by the regressors. Admittedly, setting land and non land input prices equal to zero to isolate the effects of TFP and per capita GDP is a very simplistic counterfactual that assumes no response in the land and input markets to changes in TFP as well as a perfectly inelastic demand curve in which consumers demand a fixed amount of output. Because of these limitations, the results are an upper bound of the potential effects of TFP in counteracting cropland growth due to increased demand.

In order to convey the uncertainty around these expected values, confidence intervals are obtained by randomly sampling 10,000 predictions from a multivariate normal distribution using the parameter estimates and the covariance matrix of the estimates displayed in column 1 of table 4. The 95% CI for fitted and predicted values for 1991-2000, 2001-2010, and 1991-2010 are displayed in figure 3. Focusing on the encompassing period of 1991-2010, the median predicted change in global cropland based on the predictions isolating the effect of per capita GDP, $\hat{l_{it}}^2$, labeled "Without TFP" in figure 3, indicate a cropland expansion of 181.83 Mha with a 95% CI of 101.78-270.29 Mha. The median predicted change in global cropland based on the predictions that take into account both the effect of per capita GDP as well as TFP growth, $\hat{l_{it}}^2$, labeled "With TFP", is 7.23 Mha with a 95% CI of-66.52-87.55 Mha.

A weakness of these predicted estimates is that the fixed effects may not be consistently estimated in short panels (Cameron and Trivedi, 2005, p. 738). A work around this is to calculate the difference $\hat{l_{it}}^2 - \hat{l_{it}}^1$ which eliminates the fixed effects as is based solely on the consistent estimates $\hat{\beta}_1$ and $\hat{\beta}_2$. When converted to hectares, the median estimate of the difference during 1991-2010 is 174.67 Mha with a 95% CI of 61.20-290.73 Mha.

Notwithstanding the warning about a potentially biased fixed effect, a useful way to look at these results is as the difference in cropland expansion with and without the effect of TFP growth relative to the counterfactual cropland expansion without the effect of TFP:

$$(\hat{l_{it}}^2 - \hat{l_{it}}^1)/\hat{l_{it}}^2. \tag{16}$$

This ratio measures the percentage of cropland expansion avoided by the observed patterns of TFP growth. The median values of $\hat{l_{it}}^2$ and $\hat{l_{it}}^1$ above suggest that in the absence of TFP growth, cropland expansion would have been 96.16% larger than observed. The 95% CI of the percentage of cropland expansion avoided by the observed patterns of TFP growth is bounded between 46.40% and 140.74%, suggesting, subject to the caveats of simple counterfactual analysis highlighted above and the possibility of biases in the denominator of (16), that the effect of TFP growth in counteracting increases in cropland expansion driven by increases per capita GDP is statistically significant and of considerable magnitude.

## 8.2 Land Use Effects of Asymmetric Regional Innovation

At a global level, the remaining lands with untapped potential for agriculture are in Africa, Latin America, Eastern Europe and Central Asia (Deininger and Byerlee, 2011, p. xxxiv). The effects of TFP growth in some of these regions have been the center of much attention due to the trade-offs involved in increasing agricultural productivity to improve food security and economic development in general while minimizing the impacts on the natural resource base. Ceddia et al. (2013) and Hertel, Ramankutty, and Baldos (2014) provide recent examples of these concerns in South America and Africa, both focusing on whether technological progress is associated with land savings or land expansion.

The conceptual and empirical framework above can be used to shed light on the question of where in the remaining land-abundant regions of the world would the direction of R&D investments have the greatest cropland saving effects. This question is somewhat contrived in the sense that it assumes a central planner making decisions about R&D investments in different parts of the world; in reality, private and public agencies invest in agricultural R&D according to different sets of commercial and developmental priorities. Notwithstanding the diversity of actors interested in greater agricultural productivity, there are global actors such as the agencies of the Consultative Group in International Agricultural Research as well as private donors encouraging the direction of agricultural R&D into sub-Saharan Africa (AGRA, 2017). Therefore, having a measure of the effects on agricultural land expansion relative to other regions in the world is informative.

In terms of procedure, first, within and also extra regional land supply elasticities for five aggregated regions of the world—developing Asia, South America, sub-Saharan Africa, the U.S. and Canada, and the rest of the world—are estimated using the expressions for regional and extra regional elasticities in table 1. The estimated regional elasticities are in table 5, where it can be seen, for instance, that if TFP would grow by 1% in each country in sub Saharan Africa, the expected change in cropland within the region would be -0.08%; moreover, by the market spillover effects discussed throughout the article, the expected cropland changes in other regions of the world, and in the world as whole, would be negative. In sharp contrast, the expected change in South America's cropland should every country within the region experience a 1% increase in in TFP is 0.21%. Outside the region, however, the expected changes in cropland are all negative. It is worth noting that the intra-regional elasticities have the widest confidence intervals in table 5.

A better appreciation of the effects of asymmetric regional innovation is achieved by translating the elasticities into the changes in cropland (in Mha) that would occur if TFP within some of the regions would increase by 1% in each country in the innovating region. Figure 4 displays the potential effects of a 1% country-uniform increase in TFP growth (conditional on 2001-2010 bilateral trade patterns) on cropland use in the three focus regions. Notice that 1% uniform increase of TFP in SSA would end up saving land in the region as a whole, as well as in every other region. TFP growth isolated in South America would actually entice a large expansion of the existing cropland, a finding consistent with the work of Ceddia et al. (2013). Such land expansion would be more than offset by cropland reduction in the U.S. and Canada and developing Asia, as well as in the rest of the world. If similar growth happened in developing Asia, there would be much larger land savings.

# 9 Conclusions

This study empirically investigates the extent to which changes in a country's cropland depend on changes in domestic and foreign agricultural total factor productivity. Evidence for these effects is scant. Moreover, the few existing studies investigating this issue ignore market-mediated spillovers and so fail to disentangle the effect of other drivers of land use. This dearth of evidence is of particular concern in the face of polarized perceptions about the potential for improving agricultural technologies as a means to slow down deforestation.

The analysis is built around a stylized model of bilateral international trade in the agricultural sector that yields a reduced form that is amenable to estimation using cross-country aggregate data in agricultural production, consumption, and TFP growth. The model explicitly incorporates market-mediated spillovers of land use effects across countries through the use of bilateral trade shares. An implication of the model is that, for any value of the constant elasticity of substitution among suppliers of agricultural goods, an aggregated competition index is a sufficient statistic to infer whether TFP growth would result in land savings.

The results suggest that in most countries of the world, domestic TFP growth does not have a distinguishable effect on cropland expansion. Moreover, in countries with large commodity exporting sectors, TFP growth is strongly associated with increased land expansion. It is only in the few countries in Asia and Africa that remain relatively closed to international trade that growth in domestic TFP is land saving.

Such heterogeneity of country-level outcomes disappears when we look at the global level. According to our estimates, the elasticity of global cropland with respect to changes in global TFP is negative and precisely estimated (the point estimate is close to -0.35 with a 95% confidence interval between -0.61 and -0.08). When compared to the growth in demand for agricultural products, the effect is economically meaningful. In particular, our estimates imply that had TFP growth remained stagnant from 1991 to 2010, cropland expansion would have been almost twice as large as observed (a 95% confidence interval which is between 46.40% to 140.76% larger than observed). A caveat to keep in mind is that this result is from a *ceteris paribus* regression counterfactual which assumes away responses in commodity, factor, and input markets. Further work to use the implicit structural parameter estimates in calibrating a model that depicts equilibrium in the markets underlying the structural model is likely to produce more nuanced estimates. While such an endeavor is part of our future research plans, the indicated avoided deforestation presented here should be taken as an upper bound of the potential effects.

Looking at regional levels, we find that technological progress in developing Asia and sub-Saharan Africa would reduce cropland within those regions as well as in the rest of the world. In contrast, TFP growth in South America is likely to result in expansion in regional cropland, but the net global effect is to reduce global croplands. As an additional caveat, it is necessary to point out that the focus on physical hectares is a narrow measure of the environmental effects of TFP growth. For instance, it is well known that the intensity of carbon emissions of different land cover types varies geographically, so the actual reductions depend on the composition of the global aggregate in land cover change. Other metrics, such as biodiversity, are likely to assign different weights to the value of land savings, depending on the specific region of the world where they occur. More subtle considerations, such as habitat fragmentation, may also be uncorrelated with global land savings. Studying the spillover effects of TFP on these metrics remains a fruitful area for future research.

Finally, the TFP measures used in this article may be subject to several measurement errors caused by the lack of available data. Notwithstanding this important caveat, these measures remain the only source of cross-country comparable TFP indexes over time. A potential consequence of measurement errors is the attenuation of the estimated coefficients toward zero. The strength of the significance of the regression estimates is not enough to dispel concerns about such attenuation bias, yet if this is the case, some of the estimated coefficients may be larger than discussed. A distinct possibility is that the effects of potential mismeasurement are systematic in the sample, and as a consequence, the data on TFP preserves the direction of the effects. In any case, as better data on TFP growth becomes available, the methods developed here can be readily deployed to verify the robustness of the results.

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# 10 Tables and Figures

Table 1: Elasticities of Cropland with Respect to TFP Growth at Various Geographical Scales

| Elasticity | Structural Parameters | Regression Parameters |
|---|---|---|
| Domestic ($\xi_{ii}$) | $l_i^*/z_i = -H_i\left(\lvert\eta_i^D\rvert - 1\right)$ | $\beta_1 - \beta_2 \sum_{k\neq i} \omega_{ik}$ |
| Bilateral ($\xi_{ik}$) | $l_i^*/z_k = -H_i \sigma_k \omega_{ki}$ | $\beta_2 \omega_{ki}$ |
| Foreign ($\xi_{iF}$) | $(1-\theta_i)^{-1} \sum_{k\neq i} \theta_k \xi_{ik}$ | $(1-\theta_i)^{-1} \beta_2 \sum_{k\neq i} \theta_k \omega_{ki}$ |
| Total ($\xi_i^T$) | $\theta_i \xi_{ii} + (1-\theta_i)\xi_{iF}$ | $\theta_i \beta_1 + \beta_2 \left( \sum_{k\neq i} (\theta_k \omega_{ki} - \theta_i \omega_{ik}) \right)$ |
| Intra-Regional ($\xi_{OO}$) | $\theta_O^{-1} \left( \sum_{i\in O} \theta_i \xi_{ii} + \sum_{i\in O} \sum_{(k\neq i)\in O} \theta_i \xi_{ki} \right)$ | $\beta_1 - \theta_O^{-1} \beta_2 \sum_{i\in O} \sum_{k\in O^C} \theta_i \omega_{ik}$ |
| Extra-Regional ($\xi_{OD}$) | $\theta_D^{-1} \sum_{k\in O} \sum_{i\in D} \theta_i \xi_{ki}$ | $\theta_D^{-1} \beta_2 \sum_{k\in O} \sum_{i\in D} \theta_i \omega_{ik}$ |
| Global ($\xi^W$) | $\sum_i \theta_i \left( \xi_{ii} + \sum_{k\neq i} \xi_{ki} \right)$ | $\beta_1$ |

Note: $\theta_i$ is country i's share of global cropland. $H_i = \nu_i(\nu_i + \lambda_i\phi_i)^{-1}$ where $i$ is a country index, $\nu_i$ is the land supply elasticity, $\lambda_i$ is the share of non-land inputs in total costs, and $\phi_i$ is the elasticity of substitution between land and non-land inputs. $\eta_i^D < 0$ is the elasticity of total demand (i.e., a weighted average of elasticity for the demand for domestic consumption and the bilateral demands for exports) faced by producers in country $i$. $\eta_i^D$ takes into account both domestic and foreign demand. $O$ is the innovating region and $D$ is any region outside the innovating region. The set $O^C = N - O$ is all the countries outside the innovating region.

Table 2: Descriptive Statistics

| | Min. | 1st Qu. | Median | Mean | 3rd Qu. | Max. |
|---|---|---|---|---|---|---|
| TFP Growth | -0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.05 |
| Cropland | -0.03 | -0.01 | 0.00 | 0.00 | 0.01 | 0.05 |
| Fertilizer prices | -0.20 | -0.01 | 0.02 | 0.01 | 0.04 | 0.15 |
| Land rents | -0.02 | 0.01 | 0.02 | 0.02 | 0.03 | 0.06 |
| Dom. GDP per capita | -0.01 | 0.00 | 0.01 | 0.02 | 0.02 | 0.10 |
| For. GDP per capita | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.05 |
| Cropland share of ag. suitable land | 0.06 | 0.25 | 0.48 | 0.52 | 0.72 | 1.00 |
| Domestic revenue shares | 0.00 | 0.46 | 0.74 | 0.66 | 0.89 | 1.00 |
| Domestic budget shares | 0.00 | 0.51 | 0.76 | 0.67 | 0.88 | 0.99 |

Note: Panel averages of regression variables (70 countries with two observations each). With the exception of the shares in the last three rows of the table, all the variables are average annual growth rates from 1991 to 2000 and 2001 to 2010. To be precise, let $Y_s$ denote the annual observation of $Y$ in year $s$ of a given decade. The average growth rate is $\hat{\alpha}_1$ estimated from a trend regression $ln(Y_s) = \alpha_0 + \alpha_1 \tau + \varepsilon_t$, where $\tau = 1, ..., 10$ is a trend variable.

Table 3: Ten Highest Competition Indexes in 2001-2010

| Exporter ($i$) | Competitor ($k$) | $\omega_{ik}$ | $\omega_{ki}$ |
|---|---|---|---|
| Canada | United States | 0.50 | 0.04 |
| Netherlands | France | 0.37 | 0.06 |
| Mexico | United States | 0.33 | 0.06 |
| Costa Rica | United States | 0.31 | 0.00 |
| Panama | United States | 0.30 | 0.00 |
| Netherlands | Italy | 0.30 | 0.07 |
| Netherlands | Spain | 0.26 | 0.06 |
| Honduras | United States | 0.26 | 0.00 |
| Portugal | Spain | 0.25 | 0.03 |
| Namibia | South Africa | 0.25 | 0.01 |

Table 4: Regression results.

| | *Dependent variable:* | | |
|---|---|---|---|
| | Decade-Specific Annual Cropland Growth Rate | | |
| | (1) | (2) | (3) |
| Own TFP $\beta_1$ | $-0.348^{***}$ | $-0.402^{***}$ | $-0.540^{**}$ |
| | (0.135) | (0.142) | (0.233) |
| Relative TFP $\beta_2$ | $-1.402^{***}$ | $-1.472^{***}$ | $-1.835^{***}$ |
| | (0.339) | (0.342) | (0.587) |
| Fertilizer price $\beta_3$ | $0.083^{***}$ | $0.081^{***}$ | $0.074^{***}$ |
| | (0.025) | (0.024) | (0.026) |
| Relative land rents $\beta_4$ | $-1.147^{***}$ | $-1.153^{***}$ | $-1.116^{***}$ |
| | (0.201) | (0.200) | (0.207) |
| Relative fert. price $\beta_5$ | $-0.163^{**}$ | $-0.168^{**}$ | $-0.131$ |
| | (0.083) | (0.080) | (0.086) |
| Sales-share weighted per capita GDP $\beta_6$ | $0.211^{***}$ | | $0.225^{***}$ |
| | (0.076) | | (0.076) |
| Dom. GDP per capita $\beta_{6[D]}$ | | $0.165^{**}$ | |
| | | (0.075) | |
| For. GDP per capita $\beta_{6[F]}$ | | $0.808^{***}$ | |
| | | (0.259) | |
| Cropland share $\beta_7$ | $-0.072^{***}$ | $-0.077^{***}$ | $-0.077^{***}$ |
| | (0.019) | (0.019) | (0.019) |
| Cropland share × Own TFP | | | 0.407 |
| | | | (0.323) |
| Cropland share × Relative TFP | | | 0.936 |
| | | | (0.782) |
| Observations | 140 | 140 | 140 |
| $R^2$ | 0.366 | 0.396 | 0.373 |
| Adjusted $R^2$ | 0.164 | 0.175 | 0.163 |

Note: Standard errors robust to heteroskedasticity using MacKinnon and White (1985) HC2 correction (see also Imbens and Kolesár, 2015). $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01.

Table 5: Intra and Extra Regional Elasticities of Cropland with Respect to Regional TFP Growth

| | Developing Asia | | | South America | | | Sub-Saharan Africa | | |
|---|---|---|---|---|---|---|---|---|---|
| Destination | 2.5% | 50% | 97.5% | 2.5% | 50% | 97.5% | 2.5% | 50% | 97.5% |
| U.S. & Canada | -0.12 | -0.08 | -0.04 | -0.19 | -0.13 | -0.07 | -0.02 | -0.02 | -0.01 |
| Developing Asia | **-0.42** | **-0.19** | **0.05** | -0.07 | -0.05 | -0.03 | -0.02 | -0.01 | -0.01 |
| South America | -0.09 | -0.06 | -0.03 | **-0.04** | **0.21** | **0.46** | -0.03 | -0.02 | -0.01 |
| Sub Saharan Africa | -0.05 | -0.03 | -0.02 | -0.04 | -0.03 | -0.02 | **-0.31** | **-0.08** | **0.14** |
| Rest of the World | -0.16 | -0.11 | -0.06 | -0.17 | -0.12 | -0.06 | -0.06 | -0.04 | -0.02 |
| World (as a whole) | -0.19 | -0.11 | -0.02 | -0.10 | -0.06 | -0.02 | -0.07 | -0.04 | -0.02 |

Note: Intra-Regional (in boldface) and Extra-Regional cropland elasticities with respect to TFP growth in the regions in the columns. Median values and 95% confidence intervals were calculated using the formulas in table 1 and the parameter estimates in column 1 of table 4.

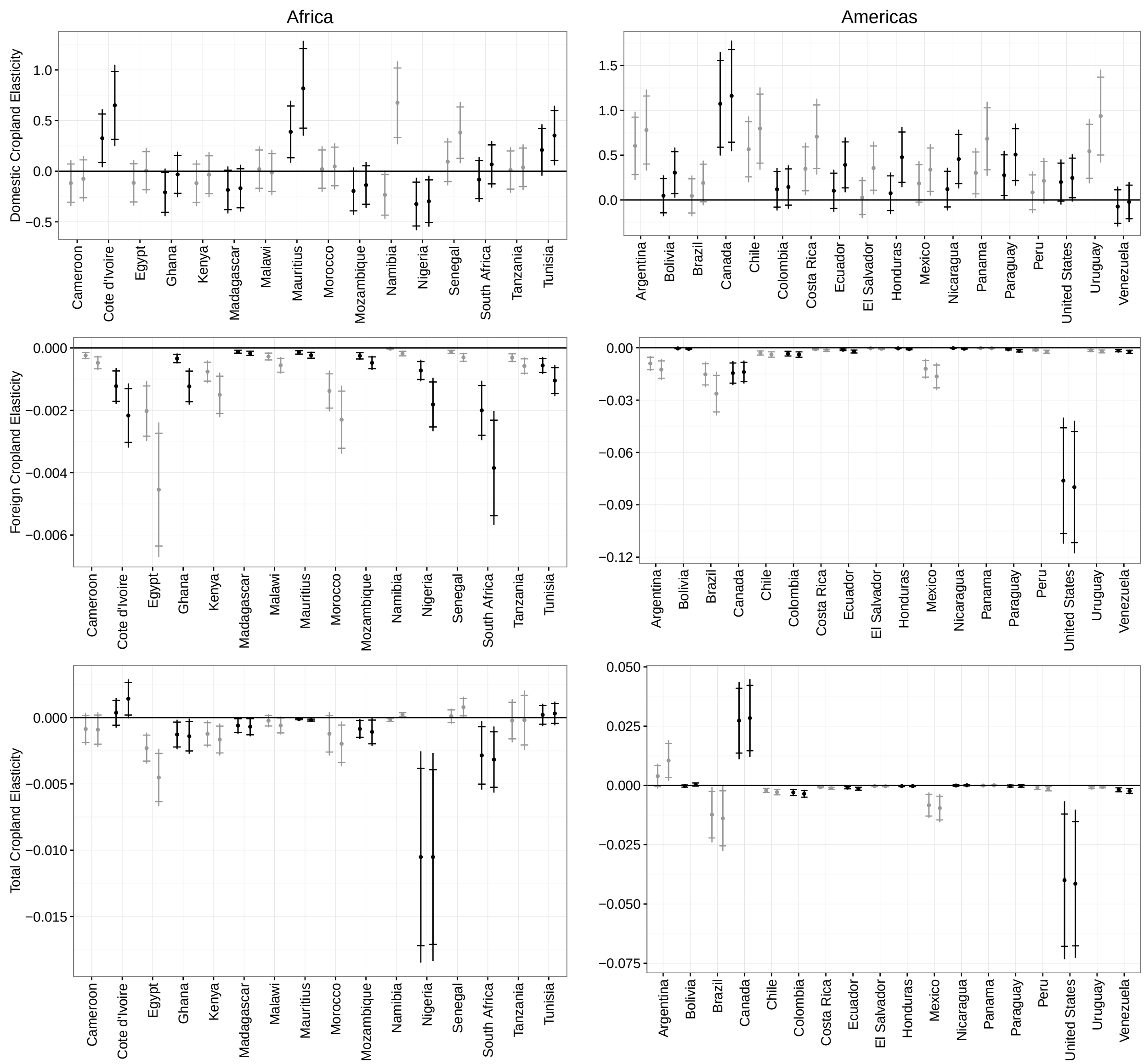


Figure 1: Estimated decennial elasticities of cropland expansion with respect to total factor productivity for all the countries in the sample.

Notes: The confidence intervals (90% identified by notches and 95% by the interval extent) are arranged in increasing order from 1991-2000 to 2001-2010.

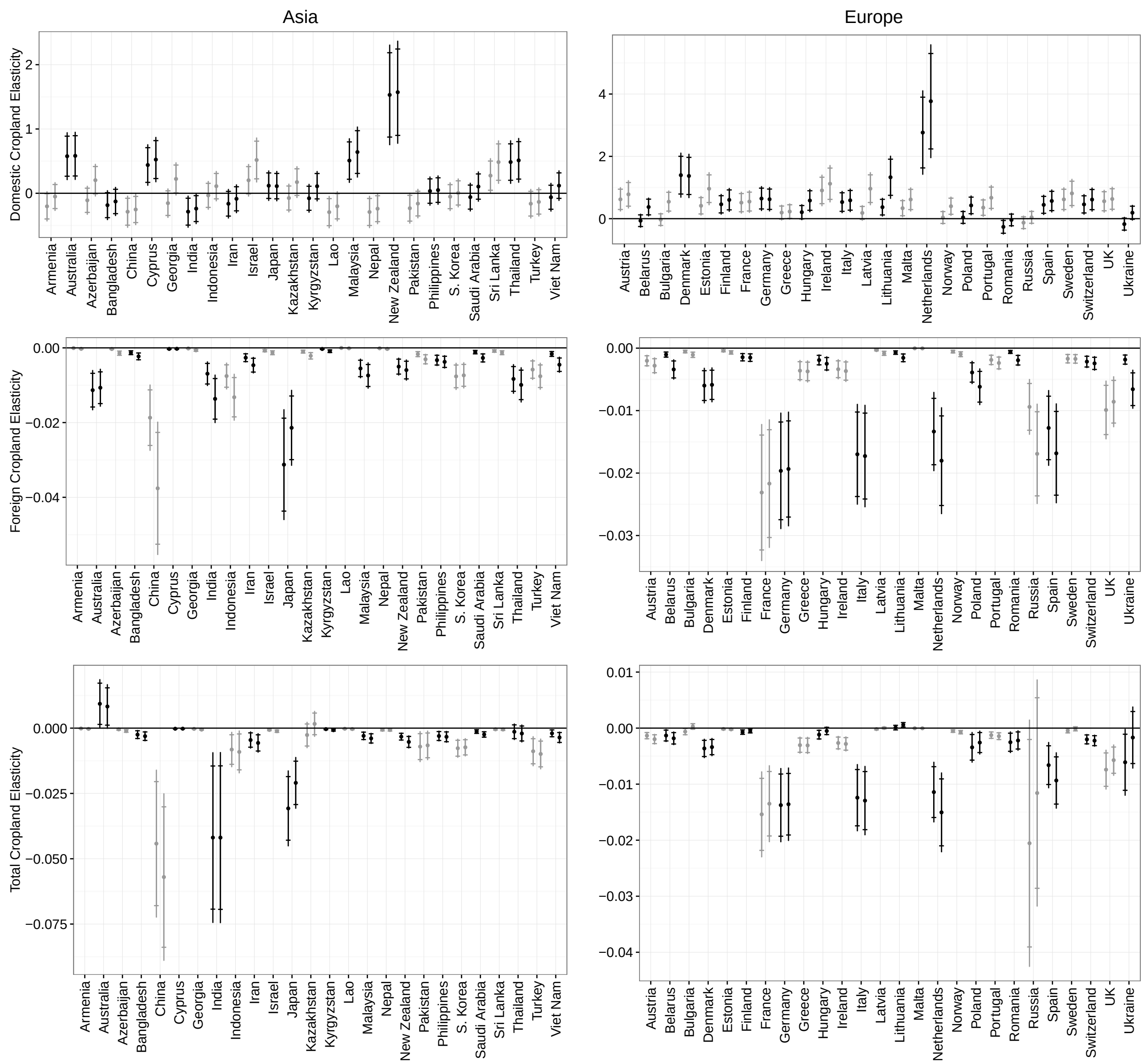


Figure 2: Estimated decennial elasticities of cropland expansion with respect to total factor productivity for all the countries in the sample.

The confidence intervals (90% identified by notches and 95% by the interval extent) are arranged in increasing order from 1991-2000 to 2001-2010.

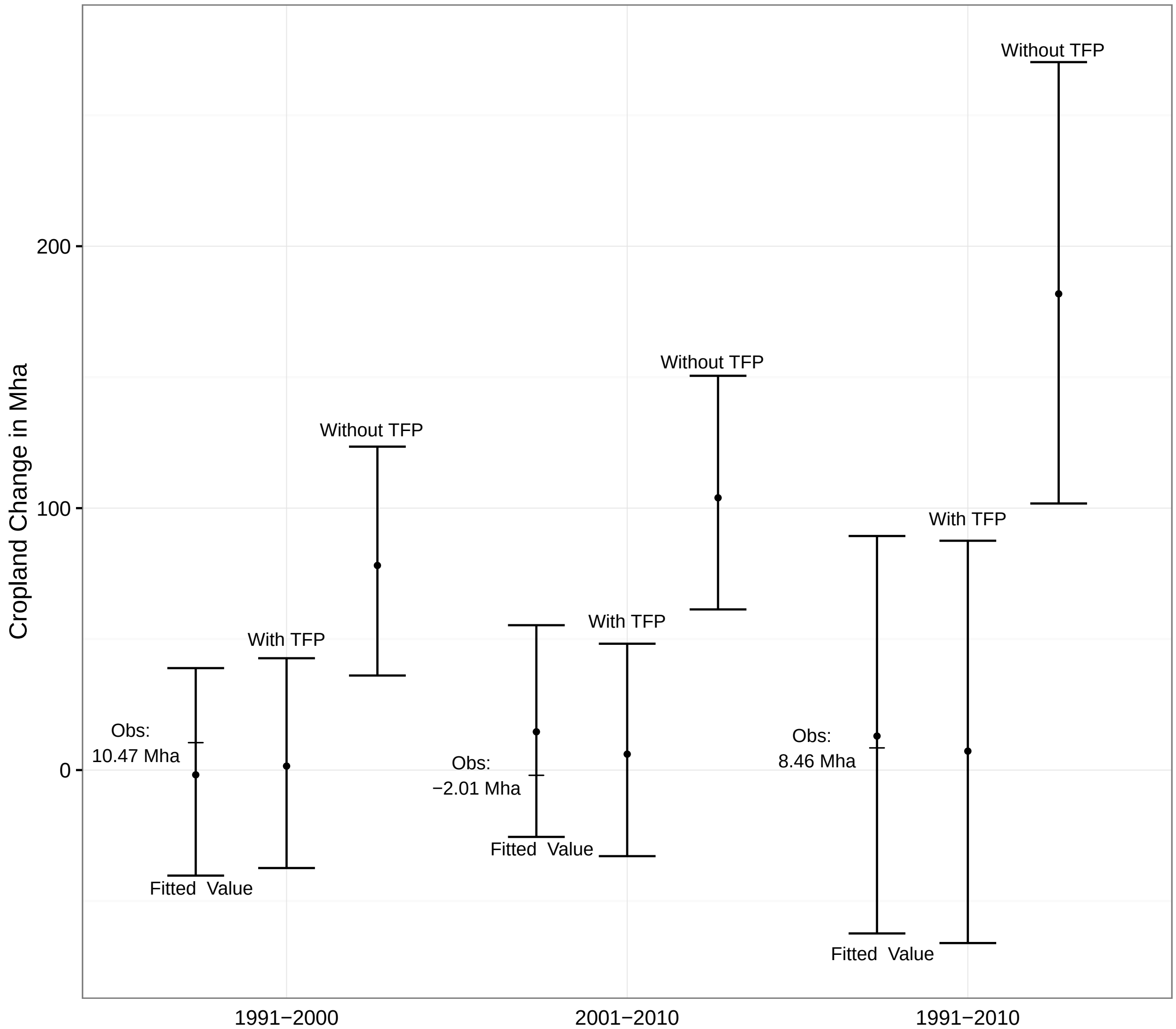


Figure 3: Simulated global cropland change with and without TFP growth.

Notes: 95% confidence intervals for predicted changes in cropland using the parameter estimates in column 1 of table 4. The changes in cropland labeled "With TFP" are obtained by adding up the fitted values of expected cropland changes in each country, $\hat{l_{it}} = E(l_{it}|z_{it}, z_{kt}, w_{it}, ..., \mu_i)$. The changes in cropland labeled "Without TFP" are obtained by adding up the predicted values of expected cropland changes in each country, $\hat{l_{it}}^{WithoutTFP} = E(l_{it}|z_{it} = 0, z_{kt} = 0, w_{it}, ..., \mu_i)$. The confidence intervals are bounded by the 0.025% and 97.5% percentiles of 10,000 randomly obtained predictions drawn from a multivariate normal, where the mean and covariance matrix are from the parameter estimates in column 1 in table 4, including the estimated fixed effects.

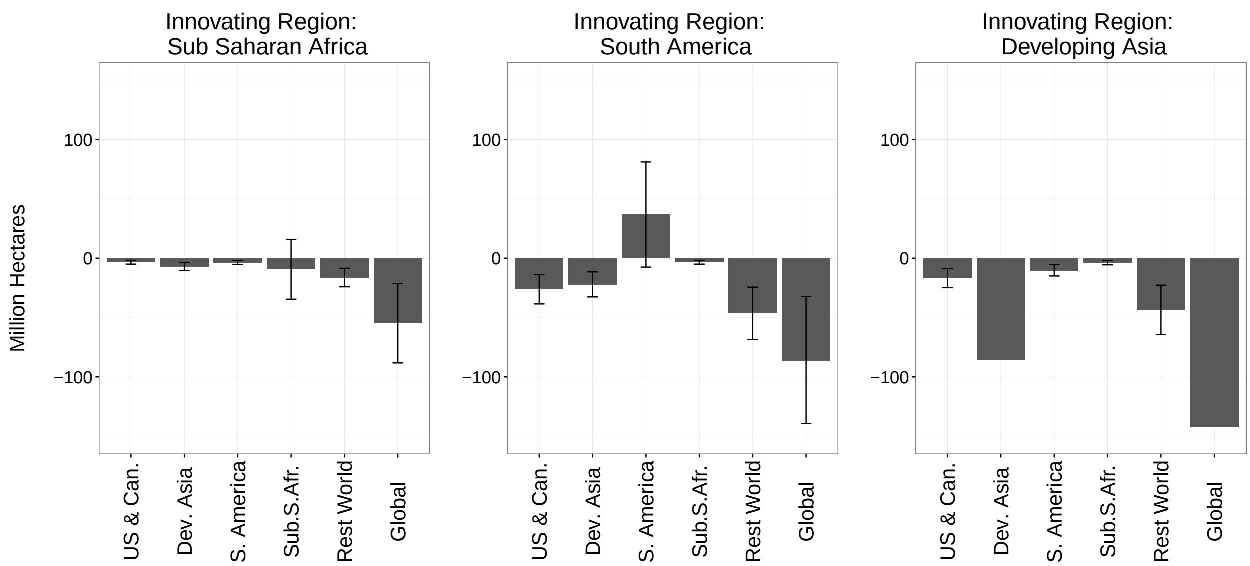


Figure 4: Change in cropland area from a 1% increase in TFP in the innovating region in the regions in the horizontal axis.

# Appendix

**GTAP Sectors**: The bilateral trade flows are from the GTAP database V.8. These were aggregated over all the agricultural sectors in the GTAP database. All the primary sectors as well as food sectors are included. Paddy rice (PDR), Wheat (WHT), Cereal grains nec (GRO), Vegetables fruit and nuts (V_F), Oil seeds (OSD), Sugar cane and sugar beet (C_B), Plant-based fibers (PFB), Crops nec (OCR), Bovine and other cattle (CTL), Animal products nec (OAP), Raw milk (RMK), Wool (WOL), Bovine meat products CMT, Meat products nec (OMT), Vegetable oils and fats (VOL), Dairy products (MIL), Processed rice (PCR), Sugar (SGR), Food products nec (OFD), Beverages and tobacco products (B_T ).

**Countries**: Argentina, Australia, Austria, Bangladesh, Bulgaria, Bolivia, Brazil, Canada, Switzerland, Chile, China, Cote d'Ivoire, Cameroon ,Colombia, Costa Rica, Germany, Denmark, Ecuador, Egypt, Spain ,Finland, France, United Kingdom, Ghana, Greece, Honduras, Hungary ,Indonesia, India, Ireland, Iran, Israel, Italy, Japan, Kenya, Korea, Lao People's Democratic Republic, Sri Lanka, Morocco, Madagascar, Mexico, Mozambique, Malawi, Malaysia, Namibia, Nigeria, Nicaragua, Netherlands, Norway, Nepal, Pakistan, Panama, Peru, Philippines, Poland, Portugal, Paraguay, Saudi Arabia ,Senegal, El Salvador, Sweden, Thailand, Tunisia, Turkey, Tanzania, Uruguay, United States, Venezuela, Viet Nam, South Africa.

**Land Rents and Non-Land Input Prices**: Obtaining implicit measures of land rents and non-land input prices involves two steps. First, aggregated costs are partitioned into the costs of land and non-land inputs using the set of cost shares provided by Fuglie (2012). Second, total costs accruing to each factor are divided by the total usage obtaining implicit real prices.

Algebraically, let $V_{it}$ denote the gross output values in country $i$ at time $t$ (under perfect competition, total costs equal total revenues, thus the gross output values from FAOSTAT are used as a measure of total costs). Further, allow for more than one non-land input (labor, livestock, machinery, fertilizer, and feed) so that $\lambda_i = \sum_l \lambda_{il}$, where $l$ denotes the $l^{th}$ non-land input. Consistent with the notation in the theory section and in the RA, land rents in country $i$ and time $t$, $R_{it}$ are estimated as:

$$R_{it} = \frac{V_{it} \times (1 - \sum_l \lambda_{il})}{L_{it}} \tag{17}$$

where $L_{it}$ are the number of quality-weighted hectares harvested in year $t$. The implicit price of the $l^{th}$ input, $W_{ilt}$ is given by:

$$W_{ilt} = \frac{V_{it} \times \lambda_{il}}{I_{ilt}}, \tag{18}$$

where $I_{ilt}$ is total input usage.

**Cropland as a share of the total area suitable for cultivation**: The area of each country that is suitable for cultivation comes from the land suitability index from Ramankutty et al. (2002). The land suitability index is the fraction of a half-degree raster pixel that is suitable for agriculture, based on the temperature and soil conditions of each pixel. The fraction of suitable land is multiplied by the hectares in each pixel, and then all the pixels within the boundaries of each country are added up to obtain the number of hectares that are suitable for agriculture.

# Reviewers' Appendix

This is the Reviewers' Appendix for the article " Technology Spillovers and Land Use Change: Empirical Evidence from Global Agriculture. " Upon publication, this appendix will be posted on line as Supplementary On-line Materials.

## S-1 Appendix to the Theoretical Framework

Unless otherwise indicated, the notations in the main text are followed throughout this appendix.

### S-1.1 Derivation of equation 4

The sub-utility function over agricultural products is assumed to take a Constant Elasticity of Substitution (CES) functional form defined over all the potential sources of agricultural products, either domestic or foreign. In levels:

$$Q_j = \left(\sum_i^n B_{ij} Q_{ij}^{\rho}\right)^{\frac{1}{\rho}}, \quad \rho = 1 - \frac{1}{\sigma}. \tag{S-1}$$

Maximization of this sub-utility function subject to a budget constraint of the form $\sum_i P_{ij}Q_{ij} < M_j$ yields bilateral demand for agricultural products, in which the first subindex refers to the supply source:

$$Q_{ij} = \frac{B_{ij}^{\sigma} M_j P_{ij}^{-\sigma}}{\sum_i^n B_{ij} P_{ij}^{1-\sigma}} = \frac{B_{ij}^{\sigma} M_j P_{ij}^{-\sigma}}{E_j^{1-\sigma}}. \tag{S-2}$$

Where $E_j$ is the CES price index.

Dual to the utility function there is an expenditure function:

$$M(\mathbf{P_{ij}}, Q_j) = \left(\sum_i^n B_{ij} P_{ij}^{1-\sigma}\right)^{\frac{1}{1-\sigma}} Q_j = E_j Q_j. \tag{S-3}$$

Intuitively, $E_j$ is the price that must be paid to attain utility $Q_j$.

Substituting the expenditure function back into bilateral demand S-2 obtains compensated demands:

$$Q_{ij} = B_{ij}^{\sigma} Q_j \left(\frac{P_{ij}}{E_j}\right)^{-\sigma}. \tag{S-4}$$

The linearized bilateral demand equation before manipulation is given by:

$$q_{ij} = d_j - \sigma\left(p_{ij} - e_j\right), \tag{S-5}$$

Starting with the price difference $p_{ij} - e_j$ in equation S-5, use $e_j = \sum_k^n \delta_{kj} p_{kj}$ (Armington, 1969, p.69)—where $\delta_{kj} = P_{kj} Q_{kj} (E_j \sum_k Q_{kj})^{-1}$, or in other words, country $j$'s total import budget spent on products from supplier $i$–referred to as budget shares—to eliminate $e_j$ to obtain: $p_{ij} - \sum_k^n \delta_{kj} p_{kj}$, where $j, k \in i$. By taking $\delta_{ij} p_{ij}$ out of the summation term in the last expression, the difference between $p_{ij}$ and the price index $e_j$ can be rewritten as $p_{ij} - \delta_{ij} p_{ij} - \sum_{k \neq i}^{n-1} \delta_{kj} p_{kj}$, which is further simplified to $p_{ij} (1 - \delta_{ij}) - \sum_{k \neq i}^{n-1} \delta_{kj} p_{kj}$. Note that $(1 - \delta_{ij}) = \sum_{k \neq i}^{n-1} \delta_{kj}$, and therefore the price difference can be rewritten once more as $p_{ij} \sum_{k \neq i}^{n-1} \delta_{kj} - \sum_{k \neq i}^{n-1} \delta_{kj} p_{kj} = \sum_{k \neq i}^{n-1} \delta_{kj} p_{ij} - \sum_{k \neq i}^{n-1} \delta_{kj} p_{kj}$. Expanding these two summation terms and regrouping them, we get the result in the text, that is, $p_{ij} - e_j = \sum_{k \neq i}^{n-1} \delta_{kj} (p_{ij} - p_{kj})$.

### S-1.2 Derivation of Equations 5 and and 6

The derivation of (5) is as follows. In the levels, $Q_i = \sum_j Q_{ij}$. However, the addition of percentage changes entails weighting each bilateral demand by the share of market $j$ in country $i$'s total sales. We refer to the sales shares as $\gamma_{ij} = \dfrac{P_{ij} Q_{ij}}{E_j \sum_i Q_{ij}}$. Using these shares, the total demand facing country $i$ is $q_i^D = \sum_j^m \gamma_{ij} q_{ij}$, where $i \in m$. Substituting $q_{ij}$ by the bilateral demands in equation 4, we obtain: $q_i^D = \sum_j^m \gamma_{ij} \left[ d_j - \sigma \left( \sum_{k \neq i}^{n-i} \delta_{kj} (p_{ij} - p_{kj}) \right), \right]$ which can be rewritten as $q_i^D = \sum_j^m \gamma_{ij} d_j - \sigma \left[ \sum_j^m \gamma_{ij} \sum_{k \neq i}^{n-i} \delta_{kj} (p_{ij} - p_{kj}) \right]$. We can further simplify the second term on the right hand side of this expression as $\sigma \left[ \sum_{k \neq i}^{n-i} \sum_j^m \gamma_{ij} \delta_{kj} (p_{ij} - p_{kj}) \right]$. More simplification is achieved by recalling the fact that $P_{ij} = P_i T_{ij}$, where $T_{ij}$ are the bilateral costs of international trade. When we transform this to percentage changes, $p_{ij} = p_i + t_{ij}$. In this application we are not concerned with trade policy shocks which may be implemented using $t_{ij}$; this means we can safely set the changes in trade costs to zero, so $t_{ij} = 0$. This simplification allows writing the substitution effect as $\sigma \left[ \sum_{k \neq i}^{n-i} \sum_j^m \gamma_{ij} \delta_{kj} (p_i - p_k) \right] = \sigma \left[ \sum_{k \neq i}^{n-i} (p_i - p_k) \sum_j^m \gamma_{ij} \delta_{kj} \right]$. The left-hand side term of this equality is used in equation S-7. As discussed in the text, the term $\sum_j^m \gamma_{ij} \delta_{kj}$ captures the competition between $i$ and $k$ in each market $j \in m$, including $i$ and $k$ markets. We conveniently denote this term by $\omega_{ik} = \sum_j^m \gamma_{ij} \delta_{kj}$, which allows for an additional simplification, a more compact simplification of the substitution effect: $\sigma \left[ \sum_{k \neq i}^{n-i} \omega_{ik} (p_i - p_k) \right]$. This expression is used in equation 6.

### S-1.3 Derivation of equation 8

Aggregate agricultural output, denoted by $Q_i$, is produced by combining land ($L_i$) and non-land inputs ($I_i$) through a CES technology:

$$Q_i = Z_i \left( I_i^{-\rho} + L_i^{-\rho} \right)^{-\frac{1}{\rho}} \tag{S-6}$$

The total costs of production are given by:

$$C_i = W_i I_i + R_i L_i. \tag{S-7}$$

To get the unit cost function, substitute the following derived demands in S-7:

$$I_i = \frac{Q_i}{Z_i}\left[\frac{1}{W_i}\right]^{\frac{1}{1+\rho}}\left[W_i^{\frac{\rho}{1+\rho}} + R_i^{\frac{\rho}{1+\rho}}\right]^{\frac{1}{\rho}}. \tag{S-8}$$

$$L_i = \frac{Q_i}{Z_i}\left[\frac{1}{R_i}\right]^{\frac{1}{1+\rho}}\left[W_i^{\frac{\rho}{1+\rho}} + R_i^{\frac{\rho}{1+\rho}}\right]^{\frac{1}{\rho}}. \tag{S-9}$$

Then divide by output $Q_i$. Step-by-step, the cost function is given by:

$$C(Q_i, W_i, R_i) = \left[W_i\left[\frac{1}{W_i}\right]^{\frac{1}{1+\rho}} + R_i\left[\frac{1}{R_i}\right]^{\frac{1}{1+\rho}}\right] \times \frac{Q_i}{Z_i}\left[W_i^{\frac{1}{1+\rho}} + R_i^{\frac{1}{1+\rho}}\right]^{\frac{1}{\rho}} \tag{S-10}$$

or:

$$C(Q_i, W_i, R_i) = \left[W_i^{\frac{\rho}{1+\rho}} + R^{\frac{\rho}{1+\rho}}\right] \times \frac{Q_i}{Z_i}\left[W_i^{\frac{1}{1+\rho}} + R_i^{\frac{1}{1+\rho}}\right]^{\frac{1}{\rho}} \tag{S-11}$$

which further reduces to:

$$C(Q_i, W_i, R_i) = \frac{Q_i}{Z_i}\left[W_i^{\frac{\rho}{1+\rho}} + R_i^{\frac{\rho}{1+\rho}}\right]^{1+\frac{1}{\rho}} \tag{S-12}$$

Now divide by output $Q_i$:

$$C(W_i, R_i) = \frac{1}{Z_i}\left[W_i^{\frac{\rho}{1+\rho}} + R_i^{\frac{\rho}{1+\rho}}\right]^{1+\frac{1}{\rho}} \tag{S-13}$$

Following Gohin and Hertel (2003), let $A = \left[W_i^{\frac{\rho}{1+\rho}} + R_i^{\frac{\rho}{1+\rho}}\right]$, and then rearrange S-13 as follows:

$$A = (Z_i C(W_i, R_i))^{\frac{\rho}{1+\rho}}. \tag{S-14}$$

And use this expression to rewrite S-8 and S-9 as follows:

$$I_i = \frac{Q_i}{Z_i}\left[\frac{1}{W_i}\right]^{\frac{1}{1+\rho}}\left[(Z_i C(W_i, R_i))^{\frac{\rho}{1+\rho}}\right]^{\frac{1}{\rho}}. \tag{S-15}$$

$$L_i = \frac{Q_i}{Z_i}\left[\frac{1}{R_i}\right]^{\frac{1}{1+\rho}}\left[(Z_i C(W_i, R_i))^{\frac{\rho}{1+\rho}}\right]^{\frac{1}{\rho}}. \tag{S-16}$$

Which can be simplified to:

$$I_i = Q_i \left[ \frac{C(W_i, R_i)}{W_i} \right]^{\phi_i} Z_i^{\phi_i - 1} \tag{S-17}$$

and

$$L_i = Q_i \left[ \frac{C(W_i, R_i)}{R_i} \right]^{\phi_i} Z_i^{\phi_i - 1}. \tag{S-18}$$

The unit cost function in percentage changes is given by Gohin and Hertel (2003):

$$c = (1 - \lambda_i) r_i + \lambda_i w - z. \tag{S-19}$$

Using lower case to denote variables in percentage changes, the derived demand for land is

$$l^D = q + \phi_i (c - r_i) + (\phi_i - 1) z \tag{S-20}$$

$$l^D = q - z_i - \phi_i (r_i - c - z_i) \tag{S-21}$$

Substitute S-19 into S-21:

$$l^D = q - z_i - \phi_i \left[ r_i \left( (1 - \lambda_i) r_i + \lambda_i w - z_i \right) - z_i \right] \tag{S-22}$$

Simplify:

$$l^D = q - z_i - \lambda_i \phi_i \left[ r_i - w_i \right]. \tag{S-23}$$

### S-1.4 Derivation of equation 10

In equilibrium, when $q_i^S = q_i^D$:

$$\frac{(\nu_i + \lambda_i \phi_i)}{\nu_i} l_i^* + z_i - \lambda_i \phi_i w_i = \sum_j^n \gamma_{ij} d_j - \sigma_i \sum_k^m \omega_{ik} \left( p_i - p_k \right) \tag{S-24}$$

Rearrange S-24 to solve for optimal land demands:

$$l_i^* = \left[ \lambda_i \phi_i w_i - z_i + \sum_j^n \gamma_{ij} d_j - \sigma_i \sum_k^m \omega_{ik} \left( p_i - p_k \right) \right] \frac{\nu_i}{(\nu_i + \lambda_i \phi_i)} \tag{S-25}$$

The percentage change in the unit cost function is actually the percentage change in prices (which implies that this also equals the percentage change in marginal costs). So rewrite S-19 as:

$$p_i = (1 - \lambda_i) r_i + \lambda_i w_i - z_i. \tag{S-26}$$

And substitute these prices into S-25:

$$l_i^* = \left[\lambda_i\phi_i w_i - z_i - \sigma_i \sum_k^m \omega_{ik}\left[(1-\lambda_i)r_i + \lambda_i w_i - z_i - (1-\lambda_i)r_k - \lambda_i w_k + z_k\right] + \sum_j^n \gamma_{ij} d_j\right] H \tag{S-27}$$

where $H = \dfrac{\nu_i}{(\nu_i + \lambda_i\phi_i)}$.

A formulation (starting from equation S-27) is to group the terms within the summation after $\sigma_i$ so they measure the relative changes in each variable:

$$l_i^* = \left[\lambda_i\phi_i w_i - z_i - \sigma_i \sum_k^m \omega_{ik}\left[(1-\lambda_i)(r_i - r_k) + \lambda_i(w_i - w_k) - (z_i - z_k)\right] + \sum_j^n \gamma_{ij} d_j\right] H \tag{S-28}$$

$$l_i^* = \left[\lambda_i\phi_i w_i - z_i - \sigma_i\left((1-\lambda_i)\sum_k^m \omega_{ik}(r_i - r_k) + \lambda_i \sum_k^m \omega_{ik}(w_i - w_k) + \sum_k^m \omega_{ik}(z_k - z_i)\right) + \sum_j^n \gamma_{ij} d_j\right] H. \tag{S-29}$$

And as before, we can express this in terms of individual terms formed by parameters and data:

$$l_i^* = H\lambda_i\phi_i w_i - Hz_i - H\sigma_i(1-\lambda_i)\sum_k^m \omega_{ik}(r_i - r_k) - H\sigma_i\lambda_i \sum_k^m \omega_{ik}(w_i - w_k) - H\sigma_i \sum_k^m \omega_{ik}(z_k - z_i) + H\sum_j^n \gamma_{ij} d_j. \tag{S-30}$$

### S-1.5 Elasticities of cropland expansion with respect to TFP

In this section, we derive foreign, total, regional, and global cropland elasticities with respect to individual, regional, and global changes in TFP. Keeping with the notation above, we use $L$ to denote cropland; e.g., $L_i$ and $L_k$ are croplands in countries $i$ and $k$. We also introduce the subscripts $F$ and $W$ to denote foreign and worldwide cropland. The relationship among the cropland in any country $i$, worldwide cropland $L_W$, and foreign cropland $L_F$ is $L_F = L_W - L_i$. We also use the term $\Delta L_{ik}$ to indicate a change in cropland in country $k$ due to the changes in TFP in country $i$. Formally:

$$\Delta L_{ik} = \xi_{ik} L_k. \tag{S-31}$$

where $\xi_{ik}$ is the elasticity of cropland in country $k$ with respect to changes in country $i$ TFP.

In what follows, in all the variables with a double subindex, the first subindex denotes the source of the TFP shock and the second subindex, a region that may be affected by that shock. So, for instance, when the interest is on changes in cropland due to changes in domestic TFP, we use $\Delta L_{ii}$:

$$\Delta L_{ii} = \xi_{ii} L_i. \tag{S-32}$$

In many cases, we are interested in the aggregated cropland effects that a given country $i$ has on aggregate foreign cropland (as opposed to the effects on a single country), so we denote these aggregated changes by $\Delta L_{iF}$, which is an abbreviated form of $\sum_{k\neq i}\Delta L_{ik}$. In other instances, the interest is on the effects of foreign changes on the TFP in country $i$'s cropland. We denote these as $\Delta L_{Fi}$ which is shorthand for $\sum_{k\neq i}\Delta L_{ki}$.

From equation 14, we can estimate the elasticity of domestic cropland with respect to changes in domestic TFP by using the estimated partial effects of decennial changes TFP ($z_i$) on decennial cropland changes ($l_i$) (we use hats to emphasize that the relevant elasticities are estimated using parameter estimates via regression):

$$\hat{\xi_{ii}} = \frac{\partial l_i}{\partial z_i} = \hat{\beta}_1 - \hat{\beta}_2\Omega_i \tag{S-33}$$

where $\Omega_i = \sum_{k\neq i}^{n-i}\omega_{ik}$. That is, the net effect of TFP in country $i$ depends on the extent to which nation $i$'s suppliers are exposed to competition with other countries. The intensity of this competition is given by adding up all the individual competition indexes $\omega_{ik} = \sum_j^m \gamma_{ij}\delta_{kj}$, where $\gamma_{ij}$ is country $i$'s sales share that measures the importance that a destination market $j$ has for $i$'s total sales of agricultural products and $\delta_{kj}$ is the share of market $j$ supplied by a competing country $k$.

In addition, we get a direct estimation of the bilateral elasticity of cropland expansion in a foreign nation $k$ with respect to changes in $i$'s TFP using the partial effect of a change in Home's TFP ($z_i$) on another countries, cropland change ($l_k$):

$$\hat{\xi_{ik}} = \frac{\partial l_k}{\partial z_i} = \hat{\beta}_2\omega_{ki}. \tag{S-34}$$

As discussed in the text, the bilateral competition indexes ($\omega_{ki}$) are not symmetric, which implies that we could have up to $n^2 - n$ non-zero bilateral elasticities. With a sample of seventy countries, these elasticities are difficult to summarize. Instead, we find it more useful to capture the indirect land use effects of changes in TFP in a given country $i$ by calculating an elasticity of foreign cropland expansion that summarizes all the land use changes abroad, which we refer to as the elasticity off foreign cropland with respect to changes in domestic TFP.

### S-1.5.1 Elasticity of foreign cropland

We find it useful to write the foreign cropland elasticity as the relative change in foreign cropland following a 1% increase in Home's TFP:

$$\xi_{iF} = \frac{\Delta L_{iF}}{L_F} = \frac{\sum_{k\neq i}\Delta L_{ik}}{L_F} = \sum_{k\neq i}\xi_{ik}\frac{L_k}{L_F}. \tag{S-35}$$

The first term on the right hand side of this expression is simply the relative change in aggregated foreign cropland. The second right hand side term makes it clear that the aggregated change abroad is the sum of the individual changes in other countries. We then use (S-31) to express the foreign cropland elasticity as a parametric expression consisting of bilateral elasticities and foreign cropland shares only. A useful simplification is achieved by writing the individual foreign cropland shares $L_k(L_F)^{-1}$ in terms of global land shares so that $L_k(L_F)^{-1} = \theta_k(1-\theta_i)^{-1}$ [4]. This allows for writing the elasticity of foreign cropland as:

$$\xi_{iF} = \frac{1}{(1-\theta_i)} \sum_{k \neq i} \theta_k \xi_{ik}, \tag{S-36}$$

where $\theta_i = L_i L_W^{-1}$ is country i's share of global cropland $L_W$. Using (S-34) to replace the bilateral elasticities in (S-36) with their regression estimates yields:

$$\hat{\xi_{iF}} = \frac{\hat{\beta}_2}{(1-\theta_i)} \sum_{k \neq i} \theta_k \omega_{ki}. \tag{S-37}$$

### S-1.5.2 Total cropland elasticity

Similarly, to derive the total cropland elasticity we find useful to start with the relative change in global cropland following a 1%t increase in country $i$'s TFP:

$$\xi_i^T = \frac{\Delta L_{iW}}{L_W} = \frac{\Delta L_{ii} + \Delta L_{iF}}{L_W} = \frac{\xi_{ii} L_{ii} + \sum_{k \neq i} \xi_{ik} L_k}{L_W} = \theta_i \xi_{ii} + \sum_{k \neq i} \theta_k \xi_{ik}. \tag{S-38}$$

This expression expresses the land use changes first in terms of the changes in domestic and foreign cropland, and then in terms of domestic and bilateral cropland elasticities as well as cropland shares, using (S-31) and (S-32) to eliminate the $\Delta$ terms. In the last right hand side term of (S-38), we use the fact that, for any country $k$, $\theta_k = L_k/L_W$. We use the foreign cropland elasticity (expression S-36) to substitute $(1-\theta_i)\xi_{iF}$ for $\sum_{k \neq i} \xi_{ik}\theta_k$, in the last term of (S-38). This reduces the overall expression to:

$$\xi_i^T = \theta_i \xi_{ii} + (1-\theta_i)\xi_{iF} \tag{S-39}$$

The empirical elasticity is obtained by substituting the own and foreign elasticities in S-39 with their regression estimates S-33 and S-37[5]:

$$\hat{\xi_i^T} = \theta_i \hat{\xi_{ii}} + (1-\theta_i)\hat{\xi_{iF}}. \tag{S-44}$$

[4] $\frac{\theta_k}{1-\theta_i} = \frac{L_k/L_W}{1-L_i/L_W} = \frac{L_k/L_W}{(L_W-L_i)/L_W} = \frac{L_k}{L_W-L_i} = \frac{L_k}{L_F}$.

[5] As with the foreign elasticity, the total elasticity can also be expressed in terms of regression parameters by substituting (S-33) and (S-37) into equation (S-39) as:

$$\hat{\xi_i^T} = \theta_i(\hat{\beta}_1 - \hat{\beta}_2\Omega_i) + (1-\theta_i)\frac{\hat{\beta}_2}{(1-\theta_i)} \sum_{k \neq i} \omega_{ki}\theta_k \tag{S-40}$$

#### S-1.5.3 Regional cropland elasticities

The cropland in a region $O$ is composed of at least two countries, so $L_O = \sum_i L_i$, where $i$ are individual countries within the region. Similarly to before, for these elasticities we assume a uniform regional TFP change of 1% within the region, which allows for the cropland elasticity of region $O$ to changes in regional TFP to be determined in terms of regional changes in cropland:

$$\xi_{OO} = \frac{\sum_k \sum_i \Delta L_{ki}}{L_O}, \forall i, k \in O. \tag{S-45}$$

where the double sum arises because for each country there are two effects: $\Delta L_{ii}$, which is the changes in country $i$'s cropland due to changes in its TFP, and $\Delta L_{ki}$ which is the change in country $i$'s cropland due to changes in country $k$'s TFP, where $k$ and $i$ are both in region $O$.

Using expressions S-31 and S-32 to eliminate the $\Delta L_{ki}$ terms in equation S-45 and multiplying the by $L_w/L_w$ yields:

$$\xi_{OO} = \frac{\sum_i \sum_k \xi_{ki} L_i}{L_O} \frac{L_W}{L_W}, \forall i, k \in O. \tag{S-46}$$

Further simplification is achieved by noting that $\theta_i = L_i/L_W$ and $\theta_O = L_O/L_W$, which is the share of global cropland accruing to the innovating region. The final expression for the regional elasticity of cropland is:

$$\xi_{OO} = \frac{1}{\theta_O} \sum_i \sum_k \theta_i \xi_{ki}, \forall i, k \in O. \tag{S-47}$$

The empirical counterpart of equation S-47 is obtained by separating own from cross TFP effects on cropland, and then substituting the estimated domestic and bilateral elasticities

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which can be simplified as (note the reversal of sub-indexes from the left-hand side to the right hand side):

$$\hat{\xi_i^T} = \theta_i \hat{\beta}_1 - \theta_i \hat{\beta}_2 \sum_{k \neq i} \omega_{ik} + \hat{\beta}_2 \sum_{k \neq i} \omega_{ki} \theta_k = \theta_i \hat{\beta}_1 + \hat{\beta}_2 \left( \sum_{k \neq i} \omega_{ki} \theta_k - \theta_i \sum_{k \neq i} \omega_{ik} \right). \tag{S-41}$$

One could also further simplify to:

$$\hat{\xi_i^T} = \theta_i \hat{\beta}_1 + \hat{\beta}_2 \left( \sum_{k \neq i} \theta_k \omega_{ki} - \sum_{k \neq i} \theta_i \omega_{ik} \right) = \theta_i \hat{\beta}_1 + \hat{\beta}_2 \left[ \sum_{k \neq i} (\theta_k \omega_{ki} - \theta_i \omega_{ik}) \right]. \tag{S-42}$$

Or could keep this one in the main text, which seem computationally simpler:

$$\hat{\xi_i^T} = \theta_i \hat{\beta}_1 + \hat{\beta}_2 \left( \sum_{k \neq i} \theta_k \omega_{ki} - \theta_i \Omega_i \right). \tag{S-43}$$

where $\Omega_i = \sum_k^m \omega_{ik}$.

from expressions S-33 and S-34 into S-47:

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\sum_i \theta_i \hat{\xi_{ii}} + \sum_i \sum_{k \neq i} \theta_i \hat{\xi}_{ki}\right] \forall i, k \in O \tag{S-48}$$

As in the other cases, further insights are gained by expressing the elasticities in terms of regression parameters and competition indexes, but their use seems limited here[6]

For the extra-regional elasticities we apply a similar procedure and define the elasticity of a non-innovating region, denoted by $D$, in terms of relative changes in regional cropland given a 1% increase in TFP in the innovating region $O$:

$$\xi_{OD} = \frac{\Delta L_{OD}}{L_D} = \frac{\sum_{i \in D} \Delta LOi}{L_D} = \frac{\sum_{k \in O} \sum_{i \in D} \Delta L_{ki}}{L_D} \tag{S-57}$$

[6]We next write out the elasticity terms as functions of parameter estimates using expressions S-33 and S-34:

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\sum_i \theta_i \left(\hat{\beta}_1 - \hat{\beta}_2 \Omega_i\right) + \hat{\beta}_2 \sum_i \sum_{k \neq i} \theta_i \omega_{ik}\right] \forall i, k \in O \tag{S-49}$$

where for any country $i$ we defined $\Omega_i = \sum_{k \neq i}^{n-i} \omega_{ik}$. Using this definition of $\Omega_i$ and regrouping terms gives:

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\sum_i \theta_i \left(\hat{\beta}_1 - \hat{\beta}_2 \sum_{k \neq i}^{n-i} \omega_{ik}\right) + \hat{\beta}_2 \sum_i \sum_{k \neq i} \theta_i \omega_{ik}\right] \forall i, k \in O \tag{S-50}$$

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\sum_i \theta_i \hat{\beta}_1 - \sum_i \theta_i \hat{\beta}_2 \sum_{k \neq i}^{n-i} \omega_{ik} + \hat{\beta}_2 \sum_i \sum_{k \neq i} \theta_i \omega_{ik}\right] \forall i, k \in O \tag{S-51}$$

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\sum_i \theta_i \hat{\beta}_1 - \hat{\beta}_2 \sum_i \theta_i \sum_{k \neq i}^{n-i} \omega_{ik} + \hat{\beta}_2 \sum_i \sum_{k \neq i} \theta_i \omega_{ik}\right] \forall i, k \in O \tag{S-52}$$

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\sum_i \theta_i \hat{\beta}_1 - \hat{\beta}_2 \sum_i \sum_{k \neq i}^{n-i} \theta_i \omega_{ik} + \hat{\beta}_2 \sum_i \sum_{k \neq i} \theta_i \omega_{ik}\right] \forall i, k \in O \tag{S-53}$$

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\hat{\beta}_1 \sum_i \theta_i - \hat{\beta}_2 \left(\sum_i \sum_{(k \in N) \neq i} \theta_i \omega_{ik} - \sum_i \sum_{(k \in O) \neq i} \theta_i \omega_{ik}\right)\right] \forall i, k \in O; O \subset N. \tag{S-54}$$

where we emphasize that the countries in region $O$ are a subset of the entire set of producing counties, denoted by $N$. Therefore, we can get an additional simplification:

$$\hat{\xi_{OO}} = \frac{1}{\theta_O}\left[\hat{\beta}_1 \sum_i \theta_i - \hat{\beta}_2 \sum_i \sum_{(k \in O^C) \neq i} \theta_i \omega_{ik}\right] \forall i \in O; k \in O^C = N - O. \tag{S-55}$$

$$\hat{\xi_{OO}} = \hat{\beta}_1 - \theta_O^{-1} \hat{\beta}_2 \sum_i \sum_{(k \in O^C) \neq i} \theta_i \omega_{ik}; \quad \forall i \in O; k \in O^C = N - O. \tag{S-56}$$

Because the originating or innovation region $O$ and the destination region $D$ do not overlap, we only need to worry about bilateral elasticities. For this, we use S-31 to eliminate the $\Delta L_{ki}$ terms in equation S-57:

$$\xi_{OD} = \frac{\sum_{k \in O} \sum_{i \in D} \xi_{ki} L_i}{L_D} \tag{S-58}$$

Multiplying the right hand side of equation S-58 by $L_W / L_W$:

$$\xi_{OD} = \frac{1}{\theta^D} \sum_{k \in O} \sum_{i \in D} \theta_i \xi_{ki} \tag{S-59}$$

with empirical counterpart given by:

$$\hat{\xi_{OD}} = \frac{1}{\theta_D} \sum_{k \in O} \sum_{i \in D} \theta_i \hat{\xi_{ki}} \tag{S-60}$$

Following the same procedures as before, we can write S-60 as a function of regression parameters by using S-34 to eliminate the bilateral elasticities:

$$\hat{\xi_{OD}} = \frac{\hat{\beta}_2}{\theta_D} \sum_{k \in O} \sum_{i \in D} \theta_i \omega_{ik} \tag{S-61}$$

### S-1.5.4 Global cropland elasticity

To estimate the global cropland elasticity, we generalize equation S-45 to include all the world:

$$\xi^W = \frac{\sum_k \sum_i \Delta L_{ki}}{L_W}. \tag{S-62}$$

which can be expressed in terms of elasticities by virtue of S-31 and also in terms of share of global cropland:

$$\xi^W = \frac{\sum_i \sum_k \xi_{ki} L_i}{L_W} = \sum_i \sum_k \theta_i \xi_{ki}. \tag{S-63}$$

As in the case of the regional elasticities, we can separate the global elasticity into domestic and foreign changes:

$$\xi^{\hat{W}} = \sum_i \theta_i \hat{\xi_{ii}} + \sum_i \sum_{k \neq i} \theta_i \hat{\xi}_{ki} \tag{S-64}$$

which can be further simplified to:

$$\xi^{\hat{W}} = \sum_i \theta_i \left( \hat{\xi_{ii}} + \sum_{k \neq i} \hat{\xi}_{ki} \right). \tag{S-65}$$

Using S-33 and S-34 on S-64, we can write the global elasticity in terms of parameters estimates:

$$\xi^{\hat{W}} = \sum_i \theta_i \left( \hat{\beta}_1 - \hat{\beta}_2 \sum_{k \neq i}^{n-i} \omega_{ik} \right) + \sum_i \sum_{k \neq i} \theta_i \hat{\beta}_2 \omega_{ik} \tag{S-66}$$

Regrouping:

$$\xi^{\hat{W}} = \sum_i \theta_i \hat{\beta}_1 - \hat{\beta}_2 \sum_i \theta_i \sum_{k \neq i}^{n-i} \omega_{ik} + \hat{\beta}_2 \sum_i \theta_i \sum_{k \neq i} \omega_{ik} \tag{S-67}$$

where $\sum_i \theta_i = 1$ so:

$$\xi^{\hat{W}} = \hat{\beta}_1. \tag{S-68}$$

which is an intuitive result because in the regression, we get the average effect of TFP on land use after controlling fro TFP spill overs.

# S-2 Results Appendix

# S-3 Notes on the calculation of relative changes and on the interpretation of regression coefficients

The data from Fuglie are annual growth rates defined as $\dot{y} = \frac{y}{dt}$ where $y = d\ln(Y) \approx \frac{dY}{Y}$. The annual growth rates are estimated by regressing the log of Y on a trend variable $t = 1, ..., T$:

$$ln(Y_t) = \alpha_0 + \alpha_1 t + \varepsilon_t \tag{S-69}$$

where $dln(Y) = \alpha_1 dt$, and therefore $\dot{y} = \alpha_1$. How can one recover the relative change in Y from $\alpha_1$ at time $T$? First, consider that $ln(\hat{Y_T}) = \hat{\alpha_0} + \hat{\alpha_1} T$, or using the exponential form, $\hat{Y_T} = \exp(\hat{\alpha_0} + \hat{\alpha_1} T)$. Because $T = 1, ..., T$, at $T = 1$, $\hat{Y_1} = \exp(\hat{\alpha_0} + \hat{\alpha_1})$. Then:

$$\frac{dY}{Y} = \frac{\exp(\hat{\alpha_0} + \hat{\alpha_1} T) - \exp(\hat{\alpha_0} + \hat{\alpha_1})}{\exp(\hat{\alpha_0} + \hat{\alpha_1})} \tag{S-70}$$

$$\frac{dY}{Y} = \exp(\hat{\alpha_0}) \frac{\exp(\hat{\alpha_1} T) - \exp(\hat{\alpha_1})}{\exp(\hat{\alpha_0} + \hat{\alpha_1})} \tag{S-71}$$

$$\frac{dY}{Y} = \frac{\exp(\hat{\alpha_1} T) - \exp(\hat{\alpha_1})}{\exp(\hat{\alpha_1})} \tag{S-72}$$

$$\frac{dY}{Y} = \exp(\hat{\alpha_1} T - \hat{\alpha_1}) - 1 \tag{S-73}$$

$$\frac{dY}{Y} = \exp(\hat{\alpha_1}(T - 1)) - 1 \tag{S-74}$$

Table S-1: Regression results for different transformations of the data.

| | *Dependent variable:* | | | |
|---|---|---|---|---|
| | Decadal change in cropland | | | |
| | PCE | PCM | PCG | PCH |
| | (1) | (2) | (3) | (4) |
| Own TFP $\beta_1$ | $-0.214$ | $-0.297^{**}$ | $-0.310^{*}$ | $-0.298^{**}$ |
| | (0.162) | (0.126) | (0.165) | (0.124) |
| Relative TFP $\beta_2$ | $-0.836^{**}$ | $-1.252^{***}$ | $-1.268^{***}$ | $-1.107^{***}$ |
| | (0.392) | (0.302) | (0.376) | (0.296) |
| Fertilizer price $\beta_3$ | 0.032 | $0.078^{**}$ | $0.068^{*}$ | $0.076^{***}$ |
| | (0.049) | (0.034) | (0.035) | (0.027) |
| Relative land rents $\beta_4$ | $-0.876^{***}$ | $-1.144^{***}$ | $-1.082^{***}$ | $-1.053^{***}$ |
| | (0.193) | (0.194) | (0.206) | (0.218) |
| Relative fert. price $\beta_5$ | 0.017 | $-0.179^{*}$ | $-0.158^{*}$ | $-0.108$ |
| | (0.101) | (0.092) | (0.091) | (0.082) |
| Dom. GDP per capita $\beta_{6[D]}$ | $0.189^{**}$ | $0.166^{**}$ | $0.206^{**}$ | $0.217^{***}$ |
| | (0.096) | (0.082) | (0.084) | (0.082) |
| For. GDP per capita $\beta_{6[F]}$ | $-0.748^{***}$ | $-0.698^{***}$ | $-0.650^{***}$ | $-0.624^{***}$ |
| | (0.165) | (0.150) | (0.175) | (0.157) |
| Observations | 140 | 140 | 140 | 140 |
| $R^2$ | 0.321 | 0.371 | 0.328 | 0.346 |
| Adjusted $R^2$ | 0.145 | 0.167 | 0.148 | 0.156 |

Note: PCE: relative changes between decennial end points. PCM: three-year averages around the initial and ending years of each decade. The 3-year moving averages are centered on the middle year of the end of each decade. For instance, the first year of the decennial 1991-2000 is the average of the observed values from 1990 to 1992, and the ending year is the average of 1999-2001. An exception was made for the decade of 2001-2010, where the final value is the average 2008-2010. PCG: decennial relative changes implied by the growth rates (See appendix S-3). PCH: Hodrick-Prescott filtered time series. This procedure is used by Fuglie (2012) to smooth the sharp fluctuations in the time series of output value and input use that underlie the cross-country calculation of TFP. Following, Fuglie (2012), a filter of 6 is used. Standard errors robust to heteroskedasticity using MacKinnon and White (1985) HC2 correction (see also Imbens and Kolesár, 2015). $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01.

We estimate the regressions with two alternative sets of transformations, relative changes and growth rates. The regression in relative changes takes the form:

$$\left(\frac{dY}{Y}\right)_t = \alpha_0 + \alpha_1 \left(\frac{dX}{X}\right)_t + \epsilon_t, \tag{S-75}$$

in which case, $\hat{\alpha_1}$ is a direct estimate of the elasticity of $Y$ with respect to $X$. For the growth rates, the regression may take the form:

$$\left(\frac{\frac{dY}{Y}}{dt}\right)_t = \alpha_0 + \alpha_1 \left(\frac{\frac{dX}{X}}{dt}\right)_t + \epsilon_t, \tag{S-76}$$

in which case $\hat{\alpha_1}$ is a direct estimate of the elasticity of $Y$ with respect to $X$.