Implications of Agricultural Productivity for Global Cropland Use and GHG Emissions: Borlaug vs. Jevons

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Abstract

This paper introduces a general framework for analyzing the impacts of regional and global technological change on long run agricultural output, prices, land rents, land use, and associated GHG emissions. In so doing, it facilitates a reconciliation of the apparently conflicting views of the impacts of agricultural productivity growth on global GHG emissions and environmental quality. As has been previously recognized, in the case of a global change in farm productivity, the critical condition for an innovation to lead to diminished land use is that the farm level demand for agricultural products is inelastic. However, in the more common case where the innovation is regional in nature, the necessary condition for a reduction in global land use and associated GHG emissions is more complex and depends on the relative yields, emissions efficiencies and supply conditions in the affected and unaffected regions. While innovations in agricultural are most common land-sparing at global scale, innovations in regions commanding a small share of global production, with relatively low yields, high land supply elasticities and low emissions efficiencies can lead to an increase in global land use change emissions. A numerical example illustrates these points and suggests that these conditions may hold for productivity shocks in Latin America and Sub-Saharan Africa. These insights are also relevant for the emerging literature on the effect of adverse climate change on global agriculture and associated emissions from land use change.

Keywords: technological progress, agricultural land use change, Jevons' paradox, land-sparing innovation, climate change impacts, greenhouse gas emissions

JEL codes: Q11, Q16, Q55, Q54

I. Motivation

There has been a resurgence of interest in the impacts of agricultural productivity on land use and the environment. At the center of this debate is Norman Borlaug's (2002) assertion that agricultural innovation is 'land-sparing'. However, the validity of this proposition rests, among other things, on his assumption of a fixed demand for food. Borlaug's hypothesis has recently been brought into questions by a series of studies of land use change which argue in favor of a competing hypothesis – dubbed "Jevons' paradox" -- which suggests that increases in agricultural productivity will be accompanied by an expansion in land area. Indeed, Angelsen and Kaimowitz (2001) express skepticism of Borlaug's 'win-win' proposition in which improved technology for agriculture results in more farm output as well as environmental improvement. Instead, they conclude their edited volume on deforestation in the tropics by suggesting that agricultural innovation often results in cropland area expansion and environmental degradation. In a further critique of Borlaug's land-sparing hypothesis, Rudel et al. (2009) scrutinize FAO data for 961 agricultural sectors in 161 countries over a 15 year period, finding little evidence of higher yields being accompanied by reduced area.

All of these studies suffer from the challenge of estimating what would have happened in the absence of such agricultural innovation. There is also a strong tendency in this literature to adopt a regional, rather than a global perspective, thereby ignoring impacts in the rest of the world, where land use and associated greenhouse gas (GHG) emissions may fall in the wake of this innovation. Accordingly, Stevenson et al. (2012) have recently revisited the land-sparing debate using a global simulation model and find that supply response in the rest of the world is a critical factor in determining the global land use impacts of technological change in one region of the world.

The debate over the impact of changes in agricultural productivity on land use has spilled over into the climate mitigation, impacts and adaptation literature. Climate change has been shown to already have had a statistically significant impact on agricultural productivity growth in many parts of the world, for several of the world's most important staple grains (David B. Lobell, Schlenker, and Costa-Roberts 2011). Warming temperatures play a particularly important role in these findings. And these temperature increases are expected to accelerate in the future. This will make it difficult to sustain productivity growth rates in the most severely affected regions. In a recent paper in *Science*, Wise et al. (2009) argue any slowdown in yield growth could have a devastating impact on land-based, GHG emissions. Indeed, they estimate that *eliminating* future crop productivity growth would result in an additional 70 Pg C of GHG emissions over the course of the 21st century. This has led to the proposition that efforts to boost agricultural yields may be an important, yet overlooked source of GHG mitigation (Lobell, Baldos, and Hertel 2012). Indeed, Burney, Davis and Lobell (2010) estimate that, between 1961 and 2005, increased yields resulted in a reduction of 161 Gt C in emissions, after netting out increased emissions owing to increased fertilizer use. These are very substantial impacts and suggest that it is important to better understand the linkages between agricultural productivity, global land use change and GHG emissions.

Most of the published results addressing the linkage between agricultural productivity, land use and GHG emissions suffer from significant flaws. Some (including Borlaug's) are simply 'back of the envelope' calculations. These are instructive, but the absence of a formal model makes it difficult to generalize the findings. Others are based on global simulation models (Wise et al. 2009; Stevenson et al. 2012), wherein the robustness of results to variation in model parameters and assumptions is often called into question. In addition, there are now quite a few individual case studies of agricultural productivity and land use change, most of which leave open the question of whether the resultant findings can be 'scaled up' for assessment of national, continental and global impacts, due to the omission of impacts in the rest of the world. What appears to be missing from this literature is an underlying analytical framework which highlights critical parameters and identifies the conditions under which Borlaug's hypothesis holds – or alternatively, the parameter configuration under which we might expect to observe Jevons' paradox. The goal of this paper is to develop a rigorous theoretical framework for analysis of these issues, laying out the conditions for Jevons' paradox, and highlighting key economic parameters governing the impact of technological innovation in agriculture on global and use and GHG emissions. This should allow researchers to focus more attention on the work that will ultimately resolve these debates, namely careful estimation of the key underlying parameters.

The framework developed here is purposely simple – yet it is also quite general in that it is compatible with a relatively wide range of views of agricultural technology, climate impacts, land supply and commodity demand. The paper begins with analysis of a single region analysis – perhaps representing a case study region, a continent or even the world as a whole. As will be seen in the numerical example, the intended scale of application will be reflected in the values of critical model parameters. Thereafter, I extend the framework to the two-region case in which, technological progress occurs in just one of the regions. This framework allows for reconciliation of many of the divergent findings in the literature, highlighting the key role of supply response in the rest of the world. The paper concludes with a numerical illustration which drives home the importance of understanding the fundamental economic parameters underpinning the regional and global supply and demand for agricultural land.

II. A simple model of long run demand and supply for agricultural land

Long run demand: Economic behavior in this farm sector model follows the approach developed in Hertel (1989), and is extended to deal with technological progress (Gohin and Hertel 2003). It is expressed in terms of cumulative percentage changes in key sector-level variables, as summarized by equations (1) - (5) in Box 1. The first equation describes long run changes in the demand for farm output as a function of *endogenous* responses to the relative scarcity of agricultural output, as measured by the change in output price, po, translated through the market price elasticity of demand, $-\varepsilon_D < 0$. The latter represents a sales-share-weighted summation of the individual elasticities associated with the different sources of demand for agricultural output.

Demand for farm inputs: The second equation in Box 1 governs the long run supply of output from the farm sector (see Gohin and Hertel (2003) for the derivation of equations (2) and (3)). In periods of depressed prices, we expect producers (and land) to exit agriculture, thereby reducing the overall supply of farm products and raising prices until they are sufficient to cover costs. In the long run no farm operator can afford to make continued losses. Similarly, in boom times, when agricultural prices are rising, we expect farmers to expand their operations, thereby bidding up the price of land until any excess profits are eliminated. With these forces in play, we expect that, over time, zero economic profits will prevail in the farm sector. This means that, once all factors of production are paid the value of their marginal product, total revenue will be exhausted. Assuming cost minimization we can express the change in unit costs in terms of the cost-share-weighted sum of input prices: $\sum_j \theta_j p_j$.

The next equation (3) in Box 1 describes the change in derived demands for agricultural inputs. Once again, this is based on the assumption that producers in the sector seek to minimize their costs in the long run. Let us continue to abstract from technological change for the moment, so we can set $a_j = ao = 0$. In the absence of technical change, there are two factors driving the demand for an input such as nitrogen fertilizer in the long run. First is the so-called *expansion effect.* This is captured by qo. If aggregate agricultural output expands by ten percent, then, all else equal, one would expect the demand for fertilizer, and indeed all other inputs, to rise by ten percent.[2] However, there is a second factor at work, the substitution effect: $\sigma(p_j - po)$. This modifies the equi-proportional expansion based on changes in the relative scarcity of inputs. (Recall from (2) that the percentage change in long run output price is equal to the percentage change in unit costs – or alternatively the average input price rise.) Thus if land becomes more scarce, we expect an intensification of fertilizer use: $q_{fert} - qo = \sigma(p_{fert} - po) < 0$, where the left hand side of this expression is the change in fertilizer intensity of agricultural output.

In the long run, what we typically observe in agriculture is that the prices of non-land inputs are dictated by the non-farm economy, which is why these are treated as exogenous in this

[2] Equation (3) reflects the phenomenon of constant returns to scale (CRTS) which suggests that a doubling of all inputs will result in a doubling of output. There is ample evidence that this does not apply at the level of individual farms. Very small farms often suffer from insufficient scale to fully exploit machinery and other modern technology. However, at the sector level, in the presence of relatively free entry/exit of firms, it can be shown that the *industry* technology will exhibit constant returns to scale (Diewert 1981).

model as in (4). The returns to agricultural land, however, are endogenous, and depend on both land demand (3) and land supply (5). As with commodity demand, the land supply response to scarcity in the farm sector is governed by an endogenous response to prices, as governed by the price elasticity of land supply with respect to land rents, ν_L .

The focus of this paper is on the impacts of technological change within this system. Technological progress is one of the key drivers of long run agricultural output and prices (Alston, Babcock, and Pardey 2010). In the simple model laid out in Box 1, there are two types of technological progress: output-augmenting, ao , and input-augmenting, a_j . In reality, technical change rarely falls into just one of these categories, but by combining shocks to ao and a_j for all N inputs, we can mimic any pattern of technological change. In the subsequent section, I focus on land-augmenting technical change (a_L) and Hicks-neutral technical change, (ao) in order to give a feel for how the type of technological change matters.

III. Analysis of Single Region Impacts

Hicks-neutral productivity shock: Setting $a_j = 0$, substituting (4) into (2), and solving for land rents, we obtain:

(6) $$p_L = \theta_L^{-1}(po + ao)$$

This is the well-known "magnification effect" in economics whereby any change in output price is magnified as it is transmitted back to the returns to the sector-specific factor, land. The degree of magnification depends on the share of these farm-owner inputs in total costs. For example, if farm-owned inputs account for half of total costs and the prices of purchased (variable) inputs are exogenous to agriculture in the long run (recall equation (4)), then, *in the face of perfectly elastic farm-level demand* (i.e. $po = 0$) , a one percent *decline* in agricultural productivity will result in a two percent decline in farm income. This magnification effect arises because farmers cannot share the burden of the adverse productivity change with purchasers of their product, nor can these burdens be passed to the suppliers of non-farm inputs, the price of which is set by the non-farm economy. Of course, if the non-farm inputs are not in perfectly elastic supply, then some of the losses will be shared with suppliers of inputs (e.g. fertilizer producers) in the form of lower prices. Because small scale, low income farm households are likely to be less commercialized, this magnification effect will typically be less pronounced for them than for commercialized farms which are well-integrated into the non-farm economy.

The notion that farmers might face a perfectly elastic demand for their products depends on the geographical scope of the productivity shock. As the span of the technological innovation expands to a global scale, the assumption that farm prices will remain unchanged becomes increasingly unrealistic. Widespread improvements in agricultural productivity (relative to their baseline realization) will result in increased global output and therefore lower prices (again, relative to baseline). The extent of the ensuing price decline will depend on the relative price elasticities of commodity supply and farm level demand – and the latter will depend on the scope of the technology shock. If the innovation is adopted on only one plot of land, then the farm level demand elasticity is likely to be very high indeed -- approaching the case of fixed commodity price as discussed in the previous paragraph. On the other hand, if the technological improvement affects the entire region, then the farm level demand elasticity will approach the consumer demand elasticity for food, which may be quite small in absolute value.

We can solve for the equilibrium outcome when commodity prices are allowed to vary as a function of the Hicks-neutral change in productivity. The easiest way to do this is to use (1) to eliminate qo from (3), and then use (2) to eliminate po. Equating (5) and (3) to reflect equilibrium in the land market leaves us with one equation in one unknown, namely land rents, which depend on all the economic parameters in the model as well as the productivity shock:

(7) $$p_L = ao\{[\varepsilon_D - 1]/[\nu_L + \sigma(1-\theta_L) + \theta_L \varepsilon_D]\} = \beta_L ao$$

Plugging (7) into (5), since land supply varies directly with land returns, we have:

(8) $$q_L = ao\{\nu_L \beta_L\}$$

Equations (7) and (8) are quite informative. Firstly, we can see that the impact of technological progress in agriculture on land supply is ambiguous. In particular, since all of the parameters in the denominator of β_L are non-negative, $ao < 0 \Rightarrow p_L > 0$ if, and only if, $\varepsilon_D < 1$. That is, *land supply and associated GHG emissions will fall following a favorable technological innovation if and only if farm level demand is inelastic.* This is is a more general statement of Borlaug's land-sparing hypothesis and confirms the findings of Angelsen and Kaimowitz (2001).

The farm level demand elasticity which is pertinent to equation (8) is directly related to the geographic scope of the productivity shocks. In those cases where the technological innovation is global in scope, such that producers worldwide are affected, then the relevant demand elasticity is the global price elasticity of demand for food -- translated back to the farm-level. Since the demand for food tends to be price-inelastic, we may conjecture that a positive innovation will reduce land area and emissions.

Given the importance of the farm level demand elasticity to the likely impacts of technological progress, it is useful to consider whether there are forces at work which are likely to change the absolute value of this price elasticity in the future. Since the bulk of agricultural output goes to food consumption, the price responsiveness of food demand is likely to be inelastic, and tends to diminish in absolute value as countries become wealthier (Seale, Regmi, and Bernstein 2003). On the other hand, the demand for biofuels, particularly at oil high prices, can be quite elastic (Buchanan, Herdt, and Tweeten, 2010; Westhoff 2010). Therefore, under some future scenarios, biofuels may be a larger contributor to ε_D than might be expected based on its modest share of total output. A notable exception will occur if the growth in biofuels is dictated by government policies, in which case this demand may become largely unresponsive to price, thereby reducing the size of the farm level demand elasticity for agricultural products.

In addition to explaining the circumstances under which cropland and GHG emissions might fall under technological innovation, (7) offers insights into the likely magnitude of such price changes. In particular, the change in land rents, for a given farm level demand elasticity and a given factor-neutral productivity shock, will be greater, the smaller the elasticity of land supply (ν_L) and the smaller the elasticity of substitution between land and non-land inputs (σ). Equation (7) can be re-written in terms of the implied commodity supply elasticity in this model: $\varepsilon_S = \theta_L^{-1}\nu_L + \sigma(\theta_L^{-1} - 1)$, where the first term represents area response to the commodity price change and the second reflects yield response to higher commodity prices. This results in (7’):

(7’) $$p_L = \{[\varepsilon_D - 1] / \theta_L[\varepsilon_S + \varepsilon_D]\}ao = \beta_L ao$$

Increasing the land supply elasticity or the elasticity of substitution boosts the aggregate supply responsiveness of output, thereby dampening the resulting price changes.

Plugging (7') into (6) and solving for the equilibrium output price change gives:

(9) $$p_O = -\{[\varepsilon_S + 1]/[\varepsilon_S + \varepsilon_D]\}ao = \beta_O ao$$

From which we see that favorable innovations will depress commodity price. The resulting equilibrium change in output can simply be read off the demand schedule:

(10) $$q_O = \varepsilon_D \beta_O ao$$

These results are summarized in the following proposition.

Proposition One: Hicks-neutral technological innovation in agriculture will increase long run land use and GHG emissions if and only if the farm level demand for output is elastic. This increase will be larger, the less important is land in total production costs, and the smaller the elasticity of substitution between land and non-land inputs.

The Case of Subsistence Producers: All of the foregoing discussion has focused on the situation where input and output markets function effectively and producers respond to market signals in determining their cost-minimizing mix of inputs. This is often the case in the highly commercialized regions where agricultural technologies are first adopted. However, if the innovation occurs in a region where the transactions costs associated with market participation are large enough to render the producers self-sufficient (de Janvry and Sadoulet 1995), then equations (1), (2), (4) and possibly even (5) are no longer relevant. Focusing on the remaining equation, (3), we can ignore the substitution effect, as that is only relevant when the farmer has access to a market for land substituting inputs. If we denote the constraining factor of production with the subscript K and set $a_j = 0, \forall j$, this leaves us with the following expression: $q_K = qo - ao = 0$. Thus, it must be the case that $qo = ao < 0$ and a 10% improvement in productivity directly into a 10% increase in output. If, in turn the subsistence farm household truly does not have access to product markets, then they must consume all they produce, so a 10% increase in food output translates directly into a 10% increase in food consumption.

Land-biased technical change: Some might argue that the primary impact of certain agricultural technologies is to alter the productivity of land – as opposed to the non-land inputs. In this case, we assume that $a_L > 0$, while $ao = 0$. Now the structure of the solution is somewhat more complex, due to the fact that this is a form of *biased* technical change, which alters the farm firms' incentives to use land vs. non-land inputs. Following the same solution strategy used above, we obtain the equilibrium changes in land rents, land use and emissions:

(11) $$p_L = \{[(\sigma - 1) + \theta_L(\varepsilon_D - \sigma)] / [(\nu_L + \sigma) + \theta_L(\varepsilon_D - \sigma)]\} a_L = \beta_{aL,L} a_L$$

When $\sigma = 0$, such that there is no scope for yield increases via increased application of non-land inputs to a given hectare of land, the term in brackets {.} simplifies considerably to: $\beta_{aL,L} = \{(\theta_L \varepsilon_D - 1) / (\nu_L + \theta_L \varepsilon_D)\}$. We can see that in this case, the condition for land supply falling in the face of productivity improvement ($\beta_{aL,L} < 0$) is less stringent than in the case of a Hicks-neutral productivity shock (*ao*), so Jevons' paradox is less likely in this case. This is because, by raising the productivity of land only, it makes land "appear" relatively less scarce to the farm firm. Mathematically, the cost share of land ($\theta_L < 1$) dilutes the price elasticity of demand, so the less dominant the land input is in production, the greater the likelihood of a decline in land use following a land-biased productivity improvement.

Allowing for non-land/land input substitution $\sigma > 0$ augments both the denominator and numerator of (11) by the term, $\sigma(1 - \theta_L)$, the absolute value of the output-constant, own-price elasticity of demand for land. Since this is positive, it renders less likely the case whereby $\beta_{aL,L} < 0$. Practically speaking, farmers can take advantage of the relative abundance of effective land by utilizing non-land inputs with less intensity. Therefore, it is less likely that the productivity improvement will result in lower land supply.

It is also useful to consider some limiting cases. As the role of non-land inputs in the farm production function diminishes ($\theta_L \to 1$), the substitution elasticity terms in both the denominator and numerator of (11) cancel out. Intuitively, land-substituting inputs become irrelevant in this case, and the condition for land supply to rise in the wake of a land-augmenting productivity gain is the same as for the Hicks-neutral productivity shock, since land is the only economically relevant factor of production when $\theta_L = 1$, and the two types of productivity changes are equivalent.

In contrast, as the land input becomes less important in production ($\theta_L \to 0$), the critical parameter in determining whether or not land use rises is σ. When $\sigma > 1$, the output-constant effect of $a_L > 0$ on firms' derived demands, as given in equation (3), is to *increase the demand for land, i.e.,* $\beta_{aL,L}^{\theta_L \to 0} > 0$. This may seem counter-intuitive, since land is more productive, one would think that less would be needed. However, with a high substitution elasticity, non-land inputs will be replaced by the relatively more efficient land input, thereby boosting demand.

Finally, consider the case when demand is perfectly elastic, such that prices are fixed. We can use (2) to deduce: $p_L = a_L$, so that any rise in land's productivity will be fully reflected in increased land rents, since there is no scope for sharing the effects of this productivity improvement in agriculture with consumers or other input suppliers.

All of these results may be translated into changes in the equilibrium use of land, agricultural output and prices, using the appropriate equations from Box 1:

(12) $q_L = \{\nu_L \beta_{aL,L}\} a_L$

(13) $po = \theta_L (p_L - a_L) = \theta_L (\beta_{aL,L} - 1) a_L = \{-(\nu_L + 1)\theta_L / [(\nu_L + \sigma) + \theta_L(\varepsilon_D - \sigma)]\} a_L$

(14) $qo = \{\varepsilon_D (\nu_L + 1) / [(\nu_L + \sigma) + \theta_L(\varepsilon_D - \sigma)]\} a_L$

So that a land-augmenting technology improvement ($a_L > 0$) can result in reduced land use (when $\beta_{aL,L} < 0$), but it must always result in lower farm prices and higher agricultural output.

In order to compare the equilibrium output change from a Hicks-neutral productivity shock to that due to the land-augmenting technical change in (14), multiply top and bottom by θ_L^{-1} and rearrange terms in the denominator in order to obtain the following, alternative expression for the supply response to the land productivity shock:

(14’) $qo = \{\varepsilon_D [\varepsilon_S - \sigma(\theta_L^{-1} - 1) + \theta_L^{-1}] / [\varepsilon_S + \varepsilon_D]\} a_L$

Where $\varepsilon_S = \theta_L^{-1}\nu_L + \sigma(\theta_L^{-1} - 1)$ is output supply response to commodity price (recall above). Comparing (10) and (14’) we see that the difference is in the numerator of the two expressions and depends on the relative importance of land in the production process, as well as the elasticity of substitution in production.

Summary of Regional Impacts Results: Table 1 summarizes the qualitative impacts of the two different types of technology change on agricultural land use and associated GHG emissions under several parametric cases of interest, including, perfectly elastic demand, fixed proportions production, and the more general case. Note from the final row of this table that the impacts of technological innovation on these variables depend on all of the model parameters in Box 1, namely, the elasticity of commodity demand, the ease of substitution in production, the share of land in total output value, and land supply response. Agricultural land use can rise in the wake of productivity improvements, but this requires that consumer demand be elastic (Hicks-neutral case), and it is even less likely when the productivity improvement is solely land-augmenting, unless there is a large elasticity of substitution between land and non-land inputs.

IV. Assessing the Impacts of Agricultural Technology on *Global* Land Use and Emissions

In the preceding section, all of the analysis focused on a single region – be it an individual farm, a province, a nation, a continent or the world. This has been the focal point of most of the existing literature. However, this single region analysis *misses the response of the rest of the world* to these developments. In order to understand the impacts of a continental scale technology shock on global land use, we need to factor in not only the changes that arise in the innovating region, but also the response of producers in the unaffected region. This broad theme has surfaced recently in the high profile debate over the global impacts of national biofuel policies. While early assessments of the GHG emissions impacts of US ethanol policies suggested that they were effective in reducing emissions (Farrell et al. 2006), later analyses that factored in the impacts on land use change and emissions in the rest of the world tended to reverse this finding (Searchinger et al. 2008; T. W. Hertel et al. 2010).

The same conceptual issue arises in the context of assessments of the potential for technological progress in agriculture to reduce global land use. While single region studies often conclude that such technological advances lead to increased land use within the affected region (Angelsen and Kaimowitz 2001), global analyses typically find that land is conserved as expansion in the benefitting region displaces production in the rest of the world (Stevenson et al. 2012). As Table 1 shows, these two results can be reconciled by appropriately adjusting the elasticity of product demand for the spatial extent of the shock. Indeed, it is for this reason that it is important to factor in the supply response of the rest of the world to regional innovation if we wish to understand the consequences for global land use change and emissions.

Global Price Effects in a Two Region Model: We begin with a reduced form representation of the preceding model, as portrayed in Figure 1, in which supply in each region is a simple function of price. With integrated world markets, an outward shift in region A's supply curve ensures an output rise in A, a fall in RoW, and a decline in world price.

Mathematically, we have:

(15) $qo^A = \varepsilon_S^A po + \Delta_S^A; \quad qo^R = \varepsilon_S^R po$ and $qo^W = \varepsilon_D^W po$

Global market clearing requires that demand equals aggregated regional supplies:

(16) $qo^W = \alpha qo^A + (1-\alpha) qo^R$

Where $\alpha = QO^A / QO^W$ denotes that share of global production in the affected region. Solving for the equilibrium change in global price in response to the shift in region A's supply curve:

(17) $$po = -\alpha\Delta_S^A / (\varepsilon_S^W + \varepsilon_D^W) = \beta_O^W ao$$

Where the global supply elasticity is just the weighted combination of the regional supply elasticities: $\varepsilon_S^W = \alpha\varepsilon_S^A + (1-\alpha)\varepsilon_S^R$.

We can now relate the two-region problem back to the single region problem dealt with previously by rewriting (17) as follows:

(18) $$po = -\Delta_S^A / (\{[\varepsilon_D^W + (1-\alpha)\varepsilon_S^R] / \alpha\} + \varepsilon_S^A) = -\Delta_S^A / (\varepsilon_D^A + \varepsilon_S^A)$$

Where $\varepsilon_D^A = [\varepsilon_D^W + (1-\alpha)\varepsilon_S^R] / \alpha$ is the *elasticity of excess demand* facing producers in region A. This reflects the residual demand for region A's product, once the supply response in the rest of the world is accounted for. As such, it is larger than the ordinary demand elasticity. Indeed, even if global demand is wholly inelastic, the excess demand response can be elastic if producers in the rest of the world are sufficiently responsive to a price change induced by developments in region *A.* Since this combined price response is weighted by the inverse of the share of region A's production in the world market, as $\alpha \to 0$, the excess demand elasticity facing these producers becomes infinite. This is simply a formal representation of the one region result in which impacts of a localized innovation in the case where the regional economy is fully integrated into the world economy results in the full benefit of the productivity improvement flowing through to producers in the innovating region.

Global Land Use Impacts: Having established the impact of a shock to supplies in region *A* on world prices, we can work our way back to the regional demands for land and ascertain the aggregated impact on global land use and GHG emissions. But before we attempt to do so, we must first be more explicit about the nature of the productivity shock in region *A*, since the type of technology change matters for the impact on land use. Throughout this section I focus on the Hicks-neutral productivity shock, as the qualitative insights from the two region model will be similar regardless of the type of shock applied in region *A*.

Referring to the model structure laid out in Box 1, the supply shift may be written as follows: $\Delta_S^A = (\varepsilon_S^A + 1)ao$. Substituting this expression into (18) gives the following price impact owing to the technology shock:

$$(19) \qquad po = -(\varepsilon_S^A + 1)ao / (\varepsilon_D^A + \varepsilon_S^A) = \beta_O ao$$

Which is identical to expression (9), excepting for the *A* superscripts on the supply and demand elasticities. These superscripts make explicit the key assumption imbedded in the earlier analysis that these shocks apply to a particular region, not to global agriculture.

With (19) in hand, the percentage change in global land use may be written as:

$$(20) \qquad q_L^W = \delta q_L^A + (1-\delta)q_L^R = \delta(\nu_L^A / \theta_L^A)(\beta_O + 1)ao + (1-\delta)(\nu_L^R / \theta_L^R)\beta_O ao$$

where $\delta = Q_L^A / Q_L^W$ is the share of the affected region's agricultural land cover in the global total, and the changes in regional land use are obtained from the regional land supply schedules.

It is not possible to say, in the general case, whether global land use change will be positive or negative following a productivity improvement in the affected region: $ao > 0$. The answer depends critically on the relative size of this region and its land supply response relative to the rest of the world. To see this, rewrite (20) as follows:

$$(21) \quad q_L^W = [\delta(\nu_L^A / \theta_L^A)(\varepsilon_D^A - 1) / (\varepsilon_D^A + \varepsilon_S^A) + (1-\delta)(\nu_L^R / \theta_L^R)(-\varepsilon_S^A - 1) / (\varepsilon_D^A + \varepsilon_S^A)]ao$$

The sign of the second term within the brackets [.] is always negative, indicating that, in the face of the inevitable price decline, owing to $ao > 0$, land area in the rest of the world will decline. The ambiguity in global land use arises due to the first term. In particular, a necessary condition for Jevon's paradox: $(q_L^W / ao) > 0$, is that the first term on the RHS of (21) be positive, and for this we require an elastic excess demand facing region *A*, $\varepsilon_D^A > 1$. However, this is not a sufficient condition. The first term must also be large enough to dominate the second one for global land use to rise in the face of technological change in region *A*. This is more likely if, in addition to the elastic excess demand (which is likely to come from having a small share of global production: $\alpha \to 0$), A comprises a relatively large land area such that $\delta \to 1$. Of course, these two conditions can only co-exist if yields are very low in the innovating region. In addition, if region *A's* land supply is relatively more responsive, i.e. $(\nu_L^A / \theta_L^A) >> (\nu_L^R / \theta_L^R)$, Jevon's paradox becomes more likely. However, since these extensive margin supply elasticities also enter into the supply and excess demand elasticities in β_O, it is difficult to say anything more precise about the conditions for global area expansion or contraction in the most general case. Therefore we turn to the analysis of some special cases in order to gain additional insight into the competing forces at work here.

Equal Extensive Margins: In the first special case, we assume that the extensive margin of supply response is equal in the two regions, i.e. $\nu_L^A / \theta_L^A = (\nu_L^R / \theta_L^R) = (\nu_L / \theta_L)$. Therefore, the terms involving $\delta(\nu_L / \theta_L)\beta_O ao$ in (20) cancel and we are left with the following expression:

(22) $$q_L^W = (\delta + \beta_O)(\nu_L / \theta_L)ao$$

Now the critical condition for Jevons' paradox is: $\delta > -\beta_O = \{[\varepsilon_S^A + 1]/[\varepsilon_S^A + \varepsilon_D^A]\}$. This is most likely to arise when the affected region is large: $\delta \to 1$, and when excess demand is very elastic: $\varepsilon_D^A >> 0$ which, as noted above, can arise when yields in the affected regions are low. Clearly having elastic global demand also makes this condition more likely, as does having a more elastic supply response in the unaffected region (*R*). In light of our assumption that the extensive margins of supply response are equal, this latter condition could arise if the intensive margin of supply response in the rest of the world is large.

Equal Intensive and Extensive Margins: To gain further insight into the conditions for global land area to decline, we can *additionally* assume that the intensive margin of supply response is identical in the two regions, so we may drop the regional subscripts in $\sigma(\theta_L^{-1} - 1)$ as well, so that: $\varepsilon_S^A = \varepsilon_S^R = \varepsilon_S^W$. Now the expression for the incidence parameter, β_O, with the full excess demand expression substituted in, becomes:

(23) $$\beta_O = -[\varepsilon_S^A + 1]/(\{[(\varepsilon_D^W + (1-\alpha)\varepsilon_S^R]/\alpha\} + \varepsilon_S^A) = -\alpha[\varepsilon_S^W + 1]/(\varepsilon_D^W + \varepsilon_S^W)$$

The condition for Jevons' paradox may therefore be written as: $\delta > \alpha[\varepsilon_S^W + 1]/(\varepsilon_D^W + \varepsilon_S^W)$ or alternatively:

(24) $\varepsilon_D^W > (\alpha/\delta)(\varepsilon_S^W + 1) - \varepsilon_S^W \Rightarrow (q_L^W / ao) > 0$

Note that the ratio of the production share to the land share in equation (24), (α/δ), reduces to the ratio of yields (output per hectare) in region *A* to global yields. Therefore, we see more clearly that the likelihood of global land area expanding in the face of innovation in region *A* increases when yields in the affected region are low, relative to the world average yields. This makes sense, since we know that agricultural area in region *R* will fall in the wake of the productivity improvement in *A*, and the area displaced by increased production in *A* will be smaller, the smaller is this yield ratio (smaller RHS in (24)) and the larger the increase in global demand due to the resultant price decline (larger LHS in (24)).

Key results from the global land use change analysis are reported in the left hand column of Table 2. From these results we deduce the following:

Proposition Two: Jevons' paradox is most likely to arise when: (a) global food demand is relatively elastic, (b) the innovating region covers a larger share of global land area, (c) yields in the affected region are relatively low,(d) the extensive margin of supply response in the innovating region is relatively large, and (e) the intensive margin of supply response in the rest of the world is large.

Global Emissions Impacts: In the literature on climate change mitigation, the reason for interest in land cover change at global scale is due to the potential for significant land-based carbon fluxes. Once we have an estimate of land cover change for each region of the world, we can attach an emissions factor to these changes, thereby obtaining an estimate of the change in global GHG emissions due to land cover change. We expect these emissions factors to depend on where the conversion occurs, previous land cover in that area, as well as the direction of conversion (i.e. into agriculture, or out of agriculture). Such nuances have now been incorporated into simulation models seeking to estimate global carbon fluxes due to land cover change (T. W.

Hertel et al. 2010; Plevin et al. 2011). For purposes of this long run analysis, it will suffice to assume that there is just one (average) emissions factor in each region, and that it is reversible – i.e. conversion of one hectare of land to agriculture releases the same amount of carbon that would be sequestered if the parcel of land were to leave agriculture. In this case, we can write the change in global emissions (E^W) as follows:

(25) $$dE^W = e^A dQ_L^A + e^R dQ_L^R$$

Where e^A is the agricultural land conversion emissions factor in region *A*, measured in tonnes of CO_2eq /hectare converted. Multiplying each of the terms on the RHS of (25) by Q_L^j / Q_L^j, and dividing through by historical emissions, defined as: $E^W = e^A Q_L^A + e^R Q_L^R$ we obtain the following expression for the change in emissions, as a percentage of historical land-based emissions:

(26) $$e^W = \gamma q_L^A + (1-\gamma) q_L^R$$

where $\gamma = e^A Q_L^A / e^W Q_L^W$ is the share of region *A* in global *historical* land-based emissions.

The percentage change in emissions may now be expressed in terms of the model parameters and the technology shock as follows:

(27) $$e^W = [\gamma(\nu_L^A / \theta_L^A)(\varepsilon_D^A - 1)/(\varepsilon_D^A + \varepsilon_S^A) + (1-\gamma)(\nu_L^R / \theta_L^R)(-\varepsilon_S^A - 1)/(\varepsilon_D^A + \varepsilon_S^A)]ao$$

Which is the same as (21), excepting that the two land use change terms are now weighted by the relative importance of each region in total potential emissions. We can then employ the same techniques for evaluating the sign of the RHS of (27) as for global land use change. Key results are summarized in the rightmost column of Table 2.

Extension of the Borlaug hypothesis to the question of emissions suggests that global land-based emissions should fall with an improvement in technology affected region. However, as with global land use, it is possible that emissions could rise. The basic conditions are the same as for global land use except for the issue of relative yields. In the case of emissions, the relevant comparison is between output/unit emissions in region *A* vs. output/unit emissions in the world as a whole. The lower this index of relative environmental efficiency in *A*, the more likely it is that global emissions could rise as a result of technological innovation in that region.

This can be readily seen if we assume that the two elements of supply response are the same in both regions, giving rise to an expression similar to (24). Now a productivity improvement in region *A* results in a rise in global emissions if:

$$(28) \qquad \varepsilon_D^W > (\alpha / \gamma)(\varepsilon_S^W + 1) - \varepsilon_S^W \Rightarrow e^W / ao > 0$$

where α / γ is the *relative emissions efficiency* of region *A.* Combining insights from the foregoing analysis, we obtain the following proposition.

Proposition Three: In general, the change in global emissions associated with agricultural land use in the face of technological improvement in a given region of the world is uncertain. However, such emissions are most likely to rise when: (a) global food demand is relatively elastic, (b) the innovating region represents a large share of historical emissions from land use change (c) the innovating region has a low relative emissions efficiency (d) the extensive margin of supply response in the innovating region is large, relative to the rest of the world and (e) the intensive margin of supply response in the rest of the world is relatively large.

V. Numerical Example

The basic concepts in this paper can be usefully illustrated with a numerical example in which the innovating region corresponds to a continent and the consequences of this regional innovation for regional and global land use and emissions are explored. In order to construct such an example, it is necessary to obtain values for production, cropland area, and GHG emissions associated with land conversion, as well as behavioral parameters describing the intensive and extensive supply response for each region (and for the rest of the world) and the global demand elasticity. This information could be obtained from a variety of sources. For convenience, I have extracted these from the long run, global partial equilibrium model of agricultural crop production documented in Baldos and Hertel (2012). In that model, there are six geographic regions of production, of which I have chosen the four listed in Table 1 for illustration here. When one of these regions is treated with a technological innovation in cropping, the rest of world is treated as an aggregation of the remaining five regions. Given the interest in long run land use change, I have chosen the authors' 15 year supply elasticities. Just to be clear, the following results are *calculations* obtained by applying these data and parameters using the equations in this paper, they do not correspond to actual model simulations.

The top panel in Table 3 reports the calculations of key parameters from tables 1 and 2. It will be evident that the regions have been listed in order of increasing importance in aggregated world crop production in the base year (2001), as reflected in FAO data. Whereas Sub-Saharan Africa (SSA) accounts for just 5.8% of global crop production, the East Asia/Pacific (EAP) region accounts for more than 30%. This has direct implications for the long run excess demand elasticity facing these regions. Whereas SSA faces a very elastic excess demand for its crops, the EAP region faces an excess demand elasticity which is only one-sixth as large (second column, top panel of Table 3). As a consequence, equation (7) predicts a smaller impact on land returns and hence land use in the EAP region. On the other hand, (19) predicts that the impact of a positive TFP shock on world price effect will be much larger for innovation in the EAP region, thereby resulting in a much larger impact on land use in the rest of the world.

In addition, from equation (26) we can see that innovation in region *A* is most likely to lead to an increase in global land use when the innovating region has relatively low yields and relatively elastic land supply response. Thus it is not be surprising that innovation in the SSA region leads to an increase in global crop land area, since average yields in that region are just 60% of the global average. In addition, SSA is a region with relatively elastic land supply, thereby further contributing to the likelihood of an increase in global cropland area. In contrast, innovation in the EAP region, with crop yields 60% above the world average, and a relatively small land supply elasticity, it is not surprising that innovation results in a significant reduction in global cropland area. If the innovation is global in scope, then the inelastic nature of global demand dictates a decline in global land use, as can be seen from the last row of Table 3.

Turning to the GHG emissions in the final column of Table 3, lower panel, the key factor is not relative yield, but rather the relative emissions efficiency factor reported in the last column of the top panel of that table. This measures the tons of output flow per ton of carbon released when forest or pasture land in the region is converted to cropland, relative to the global average. In reality, this factor is likely to vary greatly across ecosystems, so these aggregate measures are likely not very useful. West et al. (2010) document the fact that emissions efficiencies are relatively low in the tropics, a point which is highlighted by the South Asia entry. Overall, we see that global emissions from land conversion rise when technological innovations occur in the SSA and Latin America regions, and this is driven, not by the relative emissions efficiencies (which are near one in this numerical example), but rather by the large excess demand elasticity.

VI. Summary and Conclusions

This paper develops a simple, yet quite general, framework for analyzing the impacts of agricultural productivity changes on long run agricultural output, prices, land rents, land use and GHG emissions at both regional and global scales. It allows for reconciliation between two apparently conflicting views of the world – one associated with Norman Borlaug in which agricultural innovation spares agricultural land, and one loosely associated with William Jevons in which such innovations result in increased land use and associated GHG emissions. Much of the debate in the literature has revolved around the demand elasticity facing producers. Borlaug took the extreme position of fixing food demand, while those affiliated with Jevons' paradox in this context emphasized the production of agricultural commodities for price elastic world markets (Angelsen and Kaimowitz 2001). The framework developed here reconciles these two views of the world. Even though global food demand is inelastic, if the innovating region is small, relative to the world market, then producers may face an elastic demand for their products and the innovation can cause an expansion in area in the innovating region.

However, expansion of area and emissions in the innovating region by no means ensures a global expansion in these factors. Indeed, *in general* one expects the opposite to be true due to the price-inelastic nature of global food demand and because any expansion in land use in one region tends to be offset by 'leakage effects' in the rest of the world, where land use contracts. However, the two region case is complex. The impact on global land use is uncertain and is shown to depend on relative values in the innovating region and in the rest of the world, for a variety of key parameters in the model. These include: relative cropland area, relative yields, relative area responses and relative differences in the intensive margin of supply response.

In the case of global emissions, the paper concludes that innovation in one region is, once again, most likely to lead to reduced global emissions from land use change. However, it is possible that emissions from global land use change could rise when global demand is more elastic, the relative emissions efficiency of the innovating region is low, its area response to prices is high, and the intensive margin of supply response in the rest of the world is high.

The numerical example illustrates that innovation in the larger producing regions result in significant reductions in global land use and emissions, while agricultural innovation in the small, land abundant, low-yield region of Sub Saharan Africa leads to an increase in global land – albeit a small one -- with an attendant rise in global emissions. We also see that global land use may fall, while emissions nonetheless rise, as is the case in Latin America.

The results developed in this paper also have important implications for the literature on climate change impacts and adaptation. Viewing adverse climate change as negative technological progress in agriculture, the qualitative results underpinning propositions two and three may be applied to assess under what conditions global emissions will rise, thereby contributing to more rapid global warming. In this context, successful adaptation to climate change can yield mitigation benefits, by boosting yields, relative to a climate-influenced baseline, thereby moderating land use change. Lobell, Baldos and Hertel (2012) explore this issue in the context of a numerical model. They find that avoided land use change based on adaptive research and development aimed at offsetting the adverse effects of climate change can be cost-competitive with other types of mitigation. However, as might be anticipated from the numerical example in this paper, the benefits are greatest when adaptation is global in scope. Indeed, successful adaptation in low-yielding, land-abundant regions could result in more land use and negative mitigation benefits, owing to Jevons' paradox. By offering a formal framework for analysis of these relationships, this paper aims to raise the level of rigor in the debate pitting William Jevons against Norman Borlaug in the context of technological change and global agricultural land use.

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Box 1: A simple model of long run demand and supply for agricultural land

(1) $qo = -\varepsilon_D po$: demand for agricultural output

(2) $po + ao = \sum_j \theta_j (p_j - a_j)$: agricultural entry/exit; zero profits

(3) $q_j + a_j = qo - ao - \sigma(p_j - a_j - po - ao), \forall j = 1 - N$: demand for agricultural inputs

(4) $p_j = 0, \forall j \neq L$: supply of non-land inputs

(5) $q_L = \nu_L p_L$: supply of land to agriculture

Notation: All price and quantity variables represent percentage changes in the underlying indexes

qo : % change in long run agricultural output

q_j : % change in long run use of agricultural input j

ao : cumulative output-augmenting technical change in agriculture

a_j : cumulative input-*j* augmenting technical change in agriculture

po : % change in the price of agricultural output

p_j : % change in the price of agricultural input *j*

$\sigma \geq 0$: non-negative elasticity of substitution between land and non-land inputs

$\varepsilon_D \geq 0$: non-negative price elasticity of demand for aggregate farm output

$\nu_L \geq 0$: non-negative elasticity of land supply to agriculture

$\theta_j \geq 0$: non-negative cost share of input *j*

Table 1. Elasticity of Cropland (q_L) with respect to technological progress under alternative configurations of parameters

	Hicks-neutral productivity shock: $ao > 0$	Land augmenting productivity shock: $a_L > 0$
Fixed commodity prices: $\varepsilon_D \to \infty$	$\nu_L \theta_L^{-1} > 0$	$\nu_L > 0$
No substitution for land: $\sigma = 0$	$\nu_L[\varepsilon_D - 1]/[\nu_L + \theta_L \varepsilon_D]$	$\nu_L(\theta_L \varepsilon_D - 1)/(\nu_L + \theta_L \varepsilon_D)$
Unrestricted case	$\nu_L[\varepsilon_D - 1]/ [\nu_L + \sigma(1-\theta_L) + \theta_L \varepsilon_D]$	$\nu_L[(\sigma - 1) + \theta_L(\varepsilon_D - \sigma)]/$ $[(\nu_L + \sigma) + \theta_L(\varepsilon_D - \sigma)]$

Glossary of parameters:

$\sigma \geq 0$: non-negative elasticity of substitution between land and non-land inputs

$\varepsilon_D > 0$: absolute value of the price elasticity of demand for aggregate farm output

$\nu_L \geq 0$: non-negative elasticity of land supply to agriculture

$\theta_L > 0$: positive cost share of land in agricultural production

Table 2. Elasticity of global land use and emissions with respect to a Hicks-neutral productivity change ($ao > 0$) in region *A* under alternative configurations of parameters

	Global Land Use q_L^W	Global land based emissions: e_W
Unrestricted case	$[\alpha(\nu_L^A / \theta_L^A)(\varepsilon_D^A - 1) + (1-\alpha)(\nu_L^R / \theta_L^R)(-\varepsilon_S^R - 1)] / (\varepsilon_D^A + \varepsilon_S^A)$	$[\gamma(\nu_L^A / \theta_L^A)(\varepsilon_D^A - 1) + (1-\gamma)(\nu_L^R / \theta_L^R)(-\varepsilon_S^R - 1)] / (\varepsilon_D^A + \varepsilon_S^A)$
Equal land supply elasticities	$(\delta - \{[\varepsilon_S^A + 1] / [\varepsilon_S^A + \varepsilon_D^A]\})(\nu_L / \theta_L)$	$(\gamma - \{[\varepsilon_S^A + 1] / [\varepsilon_S^A + \varepsilon_D^A]\})(\nu_L / \theta_L)$
Equal extensive & intensive supply elasticities	$(\delta - \alpha[\varepsilon_S^W + 1] / (\varepsilon_D + \varepsilon_S^W))(\nu_L / \theta_L)$	$(\gamma - \alpha[\varepsilon_S^W + 1] / (\varepsilon_D + \varepsilon_S^W))(\nu_L / \theta_L)$

Glossary of parameters:

$\varepsilon_D > 0$: absolute value of the global price elasticity of demand for aggregate farm output

$\varepsilon_D^A > 0$: excess demand elasticity for farm output in region *A*

$\varepsilon_S^j > 0$: supply elasticity of farm output in region *j = A, R or W*

$\nu_L \geq 0$: non-negative elasticity of land supply to agriculture

$\theta_L > 0$: positive cost share of land in agricultural production

$\alpha > 0$: share of region *A* agricultural output in global total

$\delta > 0$: share of region *A* agricultural land cover in global total

$\gamma > 0$: share of region *A* potential emissions in global total

Table 3. Impact of technological progress on global agriculture

	Parameters: 15 year supply response			
Region	Production Share	Excess Demand Elasticity	Relative Yield	Relative Emissions Efficiency
Sub-Saharan Africa	0.058	16.968	0.596	1.005
Latin America	0.120	7.605	1.117	1.063
South Asia	0.148	6.382	0.965	0.867
Easia-Pacific	0.307	2.765	1.596	1.084
World	1.000	0.125	1.000	1.000

Source: Parameters adapted from Baldos and Hertel (2012) to reflect the model structure in Box 1, while matching regional supply response at the intensive and extensive margins.

	Impact of 1% TFP on selected variables			
	World	Land Use		Emissons
Region	Price	Region A	World	MMtCO2e
Sub-Saharan Africa	-0.14	1.029	0.028	50
Latin America	-0.26	0.797	-0.039	59
South Asia	-0.26	0.504	-0.036	-5
Easia-Pacific	-0.50	0.237	-0.206	-394
World	-1.81	n.a.	-0.483	-1263

Source: Impacts calculated using equations in paper

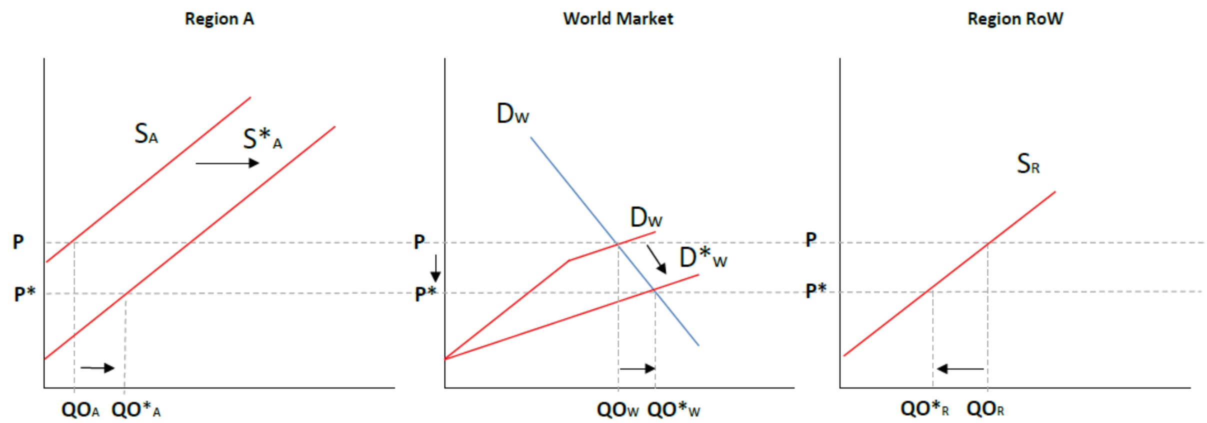

Figure 1. Impact of technical change in Region A on global supplies and price