Supporting Information

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SI Text

Simplified International Model of Prices Land Use and the Environment Model. In the model (Fig. S1), per capita consumer demands for three food types, crops, livestock, and processed foods, are log-linear functions of price and income, with respective food demand elasticities varying as a function of per capita income in each region. Based on international cross-sectional estimates by Muhammad et al. (1), the absolute values of the income and price elasticities for all food types fall as incomes grow. Regional food demand is obtained by multiplying per capita demand by regional population. Because livestock and processed foods are valued-added products, these are produced within the consuming region using crop and noncrop inputs and therefore have region-specific prices. A substantial share of crop demands in the model is derived demands, obtained from the consumer demands for value-added food products. This distinction is important, because technological change and factor substitution in the livestock and processed food industries can lead to varying intensities of crop use in these food products. The global demand for crops is the summation of final demands and derived demands summed over all regions. World demand for crop feedstocks in biofuels is exogenously specified and serves as an addition to global crop demand.

Global crop production in the model is specified for each of the 15 geographic regions as a constant elasticity of substitution function of land and nonland inputs, each with different yields and potentially differing rates of technological progress. Cropland supply elasticities, which vary by region, are based on the adjusted estimates of Gurgel et al. (2) and Ahmed et al. (3). Nonland factor supplies to agriculture are also less than perfectly elastic supply, but are more price responsive than land supply, based on the estimates offered by The Organization for Economic Cooperation and Development (4). In the standard version of the Simplified International Model of Prices Land use and the Environment (SIMPLE) model, equilibrium is attained in the crop markets when supply equals demand, where the equilibrating variable is the global price of crops. In this paper, we implement market segmentation in the SIMPLE model via a finite elasticity of substitution between crop commodities in the domestic and international markets.

The extent of market segmentation in the model is based on historical evidence regarding the substitutability of goods in international trade (5), and the error bars reflect the underlying uncertainty in these historical estimates. However, given the importance of this assumption, it is useful to consider the implications of changing it. In the most extreme case, namely that in which regional markets are entirely independent, supply must equal demand at the regional level. The land-sparing condition is then simply given by Eq. **1** in which the price elasticity of demand for crops in the innovating region must be less than one. This price elasticity condition strikes us as quite likely for staple crops. As crop price transmission across borders increases, the excess demand elasticity facing the innovating region will be increased as the responsiveness of producers in RoW is rises. This increased excess demand elasticity raises the likelihood that land use in the innovating region will increase, thereby leading to Jevons' paradox (Eq. **1**). Although global markets have not been integrated historically, the future is likely to see increasing market integration.

Calculation of Emissions Factors. The carbon loss per hectare of cropland (including emission efficiency factors) is calculated using grid-cell crop dry yield and carbon loss data from West et al. (6). To aggregate grid cell data across 15 regions in SIMPLE, we weight both pixel-based measures by the actual amount of available land for clearing. This availability has two components: (*i*) within each currently cropped pixel, the available land is computed as pixel area less current extent of cropland; and (*ii*) within each noncropped pixel within each region, the available land equals the total pixel area. However, some of these noncropped pixels could be considered inaccessible, so we only consider pixels adjacent to currently cropped pixels when calculating the emissions efficiencies.

Monte Carlo Analysis with Respect to Model Parameters. Sensitivity analysis on the model outcomes is conducted via Monte Carlo simulations (Tables S1 and S2). Inputs to each simulation are drawn from independent triangular distributions of eight global parameters (Table S1). Parameters that guide consumption and production behavior in SIMPLE are taken from several sources. Demand elasticities in the model consist of income and price elasticities (EIY and EIP, respectively) for each food commodity (i.e., crops, livestock and processed foods). These elasticities are based on the country-level estimates by Muhammad et al. (1). Production parameters in SIMPLE include the following: the price elasticity of nonland input supply (ENLAND), derived from Keeney and Hertel (7), and the 15-y price elasticity of US land supply (ELAND), which was taken from Ahmed et al. (3). We do not have robust estimates of the unobserved intensification parameters (i.e., elasticities of substitution) in crop and livestock production; hence, we rely on model calibration to derive these parameters. The elasticity of substitution between land and nonland inputs in crop production (ECROP) is calibrated separately for the historical and future simulations. In the former, this parameter is calibrated by targeting observed global cropland expansion from 1961 to 2006, whereas in the latter, this is done by ensuring that the economic yield response to crop prices in the model matches the estimate from Keeney and Hertel (8), i.e., a 1% increase in global crop price translates to a 0.25% increase in global crop yields. For the elasticity of substitution in the livestock sector (ECRPFEED), we rely on the methods outlined in Baldos and Hertel (9), albeit using updated data. The Armington elasticity (ESUB) that governs the substitution between domestic and global crop commodities for both consumers and producers is based on the average for all crops taken from the GTAP parameter file (10). Carbon loss per hectare (C_EMIS_HA) is derived from West et al. (6) as previously outlined.

Some parameters are converted to regional values using regional scalars (Table S2), which are used to scale up or down a global parameter. This scaling reflects the notion that if the true income elasticity of demand for livestock in one region is higher than in the base case, then all of them are too high, because these are derived from the same global study. Scalars of the land supply elasticity are constructed using on the variations in the regional elasticities of land supply from Gurgel et al. (2) as a guide. Regional scalars for the carbon loss per hectare of cropland are computed using the methods and data mentioned above.

Our sample size is 1,000 experiments. Except for the Armington elasticities, the maximum and minimum of all parameter distributions are constructed using the assumption that these are ±30% away from the mode due to limited empirical evidence. The range of the Armington elasticities is based on maximum and minimum values found in the GTAP parameter file for different individual crop sectors (10).

Robustness Results for the Historical Green Revolution. Fig. 2 reports percent changes under the historical baseline: 1961–2006[*] [inclusive of the Green Revolution (GR)], as well as for the no-GR counterfactual scenario. On the other hand, Fig. S2 reports the actual differences (i.e., GR – no-GR) in global and regional land use and CO_2 emissions, along with the error bars denoting the 95% CIs. From these results, it is clear that the historical GR was both land and emissions sparing given the uncertainty in model parameters, with mean reductions of 144 Mha and 1,306 MMg CO_2, respectively.

Derivation of Eqs. 1–3 in the Text. In the theoretical model, there are a number of key parameters that will be important. These parameters are summarized in Table S4 for the sake of convenience.

Key Behavioral Relationships in the Theoretical Model. ***Long run demand.*** Economic behavior in this farm sector model follows the approach developed in Hertel (11) and is extended to deal with technological progress (12). It is expressed in terms of cumulative percentage changes in key sector-level variables, as summarized in Box S1. The first equation describes the long run changes in the demand for crops 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 farm-level 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 crops (direct consumption, livestock use and processed foods, in the case of SIMPLE).

Box S1. Analytical model of long run demand and supply for agricultural land

(1) $qo = -\varepsilon_D po$	Demand for agricultural output
(2) $po + t = \sum_j \theta_j p_j$	Agricultural entry/exit; zero profits
(3) $q_j = qo - t - \sigma(p_j - po - t)$, $\forall j = 1 - N$	Demand for agricultural inputs
(4) $p_j = 0$, $\forall j \neq L$	Supply of nonland 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; t, cumulative output-augmenting technical change in agriculture; po, % change in the price of agricultural output; p_j, % change in the price of agricultural input j; $\sigma \geq 0$, nonnegative elasticity of substitution between land and nonland inputs; $\varepsilon_D \geq 0$, nonnegative price elasticity of demand for aggregate farm output; $\nu_L \geq 0$, nonnegative elasticity of land supply to agriculture; $\theta_j \geq 0$, nonnegative cost share of input j.

Demand for farm inputs. The second equation in Box S1 governs the long run supply of output from the farm sector (see ref. 18 for the derivation of Eqs. **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 condition 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 third equation in Box S1 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. 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 effect is captured by qo. If aggregate agricultural output expands by 10%, then, with all else equal, one would expect the demand for fertilizer, and indeed all other inputs, to rise by 10%.[†] However, there is a second factor at work, the substitution effect: $\sigma(p_j - po)$. This effect modifies the equi-proportional expansion based on changes in the relative scarcity of inputs. (Recall from Eq. **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 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 nonland inputs are dictated by the nonfarm economy, which is why these are treated as exogenous in this model as in the fourth equation in Box S1. The returns to agricultural land, however, are endogenous, and depend on both land demand (third equation of Box S1) and land supply (fifth equation of Box S1). 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 analysis is on the impacts of technological change, which is a key driver of long run agricultural output and prices (14). In the theoretical model laid out in Box S1, there is just one type of technological progress: output-augmenting, t, or Hicks-neutral technical change, which is the predominant type explored in the literature.

Analysis of Single Region Impacts. Substituting equation 4 in Box S1 into equation 2 in Box S1, and solving for land rents, we obtain

$$p_L = \theta_L^{-1}(po + t). \qquad \textbf{[S1]}$$

This result 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 equation 4 in Box S1, then, in the face of perfectly elastic farm-level demand (i.e., $po = 0$), a 1% decline in agricultural productivity will result in a 2% 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 nonfarm inputs, the price of which is set by the nonfarm economy. Of course, if the nonfarm inputs are not in perfectly elastic supply, then some of the losses will be shared with suppliers of inputs (e.g., fertilizer

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[*] For the historical analysis, we start with the 2006 database then create the 1961 database via hindcasting. However, the results are reported as changes from 1961-2006 for ease of interpretation.

[†] Eq. **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 (13).

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 nonfarm 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 the first equation in Box S1 to eliminate *qo* from the third equation, and then use the second equation to eliminate *po*. Equating the third and fifth equations in Box S1 to reflect equilibrium in the land market leaves us with one equation in one unknown, namely land rents, which depend on all of the economic parameters in the model as well as the productivity shock:

$$p_L = t\{[\varepsilon_D - 1]/[\nu_L + \sigma(1-\theta_L) + \theta_L\varepsilon_D]\} = \beta_L t. \qquad \textbf{[S2]}$$

Plugging Eq. **S2** into the equation 5 in Box S1, because land supply varies directly with land returns, we obtain

$$q_L = t\{\nu_L\beta_L\}. \qquad \textbf{[S3]}$$

Substituting in the expression for β_L and rearranging, as well as adding superscripts to denote the fact that we are considering a worldwide change in technology, we obtain Eq. **1**. We can see that the impact of technological progress in agriculture on land supply is ambiguous. In particular, because all of the parameters in the denominator of β_L are nonnegative, $t > 0 \Rightarrow p_L < 0$ if, and only if $\varepsilon_D < 1$. That is, land supply and associated greenhouse gas (GHG) emissions will fall following a favorable technological innovation if and only if farm level demand is inelastic. This condition is a more general statement of Borlaug's land-sparing hypothesis and confirms the findings of Angelsen and Kaimowitz (15).

The farm level demand elasticity which is pertinent to Eq. **1** 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. Because the demand for food tends to be price inelastic, we may conjecture that a positive innovation will reduce land area and emissions.

In addition to explaining the circumstances under which cropland and GHG emissions might fall under technological innovation, Eq. **S2** 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 and the smaller the elasticity of land supply (ν_L) and the smaller the elasticity of substitution between land and nonland inputs (σ) will be. Eq. **S2** can be rewritten 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 substitution results in Eq. **S4**

$$p_L = \{[\varepsilon_D - 1]/\theta_L[\varepsilon_S + \varepsilon_D]\}t = \beta_L t. \qquad \textbf{[S4]}$$

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

Plugging Eq. **S4** into Eq. **S1** and solving for the equilibrium output price change gives

$$po = -\{[\varepsilon_S + 1]/[\varepsilon_S + \varepsilon_D]\}t = \beta_O t, \qquad \textbf{[S5]}$$

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

$$qo = \varepsilon_D\beta_O t. \qquad \textbf{[S6]}$$

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. However, when the relevant scale is less than global, this single region analysis *misses* the response of the rest of the world to these developments. 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.

Global price effects in a two-region model. We begin with a reduced form representation of the preceding model, as portrayed in Fig. 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 the rest of the world (RoW), and a decline in world price.

Mathematically, we have

$$qo^A = \varepsilon_S^A po + \Delta_S^A, \quad qo^R = \varepsilon_S^R po, \quad \text{and} \quad qo^W = \varepsilon_D^W po. \qquad \textbf{[S7]}$$

Global market clearing requires that demand equals aggregated regional supplies

$$qo^W = \alpha qo^A + (1-\alpha)qo^R, \qquad \textbf{[S8]}$$

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

$$po = -\alpha\Delta_S^A \big/ \left(\varepsilon_S^W + \varepsilon_D^W\right) = \beta_O^W t^A. \qquad \textbf{[S9]}$$

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 Eq. **S9** as follows:

$$po = -\Delta_S^A \big/ \left(\left\{\left[\varepsilon_D^W + (1-\alpha)\varepsilon_S^R\right]/\alpha\right\} + \varepsilon_S^A\right) = -\Delta_S^A \big/ \left(\varepsilon_D^A + \varepsilon_S^A\right), \qquad \textbf{[S10]}$$

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 elasticity 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*. Because 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 result 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. However, before we attempt to do so, we must first be more explicit about the nature of the productivity shock in region A, because the type of technology change matters for the impact on land use. Throughout this section, we 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 S1, the supply shift may be written as follows: $\Delta_S^A = (\varepsilon_S^A + 1)t^A$. Substituting this expression into Eq. **S10** gives the following price impact owing to the technology shock:

$$po = -\left(\varepsilon_S^A + 1\right)t^A / \left(\varepsilon_D^A + \varepsilon_S^A\right) = \beta_O t^A, \qquad \textbf{[S11]}$$

which is identical to Eq. **S5**, 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 Eq. **S11** in hand, the percentage change in global land use may be written as

$$q_L^W = \delta q_L^A + (1-\delta) q_L^R = \delta\left(\nu_L^A/\theta_L^A\right)(\beta_O + 1)t^A + (1-\delta)\left(\nu_L^R/\theta_L^R\right)\beta_O t^A, \qquad \textbf{[S12]}$$

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.

As noted in the main text, 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 Eq. **S12** as follows:

$$\begin{aligned} q_L^W/t^A = \Big[&\delta\left(\nu_L^A/\theta_L^A\right)\left(\varepsilon_D^A - 1\right)/\left(\varepsilon_D^A + \varepsilon_S^A\right) \\ &+ (1-\delta)\left(\nu_L^R/\theta_L^R\right)\left(-\varepsilon_S^A - 1\right)/\left(\varepsilon_D^A + \varepsilon_S^A\right)\Big], \end{aligned} \qquad \textbf{[S13]}$$

which is Eq. **2**. The sign of the second term within the brackets [] is always negative, indicating that, in the face of the inevitable price decline, owing to $t^A > 0$, 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: $(q_L^W/t^A) > 0$, is that the first term on the right side of Eq. **S13** 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 condition 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 coexist if yields are very low in the innovating region. In addition, if region A*'s* land supply is relatively more responsive, i.e., $(\nu_L^A/\theta_L^A) \gg (\nu_L^R/\theta_L^R)$, Jevon's paradox becomes more likely. However, because 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 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 $\delta(\nu_L/\theta_L)\beta_O t^A$ in Eq. **S12** cancel and we are left with the following expression:

$$q_L^W = (\delta + \beta_O)(\nu_L/\theta_L)t^A. \qquad \textbf{[S14]}$$

Now the critical condition for Jevons' paradox is $\delta > -\beta_O = \{[\varepsilon_S^A + 1]/[\varepsilon_S^A + \varepsilon_D^A]\}$. This condition is most likely to arise when the affected region is large, $\delta \to 1$, and when excess demand is very elastic: $\varepsilon_D^A \gg 0$, 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 (RoW). 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 $\varepsilon_S^A = \varepsilon_S^{RoW} = \varepsilon_S^W$. Now the expression for the incidence parameter, β_O, with the full excess demand expression substituted in, becomes

$$\begin{aligned} \beta_O &= -\left[\varepsilon_S^A + 1\right] / \left[\left(\left\{\left[\varepsilon_D^W + (1-\alpha)\right]\varepsilon_S^{RoW}\right\}/\alpha\right) + \varepsilon_S^A\right] \\ &= -\alpha\left[\varepsilon_S^W + 1\right] / \left(\varepsilon_D^W + \varepsilon_S^W\right). \end{aligned} \qquad \textbf{[S15]}$$

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

$$\varepsilon_D^W > (\alpha/\delta)\left(\varepsilon_S^W + 1\right) - \varepsilon_S^W \Rightarrow \left(q_L^W/t^A\right) > 0. \qquad \textbf{[S16]}$$

The ratio of the production share to the land share in Eq. **S16**, (α/δ), reduces to the ratio of yields (output per hectare) in region A to global yields, which gives us Eq. **3**. From this, 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 condition makes sense, because we know that agricultural area in region RoW 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 right side in Eq. **2**) and the larger the increase in global demand due to the resultant price decline (larger left side in Eq. **2**).

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 (16, 17). 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:

$$dE^W = ef^A dQ_L^A + ef^R dQ_L^R, \qquad \textbf{[S17]}$$

where ef^A is the agricultural land conversion emissions factor in region A, measured in tons of CO_2 per hectare converted. Multiplying each of the terms on the right side of Eq. **S17** by Q_L^j/Q_L^j, and dividing through by historical emissions, defined as $E^W = ef^A Q_L^A + ef^R Q_L^R$, we obtain the following expression for the change in emissions, as a percentage of historical land-based emissions:

$$e^W = \gamma q_L^A + (1-\gamma) q_L^R, \qquad \textbf{[S18]}$$

where $\gamma = ef^A Q_L^A / ef^W Q_L^W$ 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:

$$\begin{aligned} e_W = \Big[&\gamma \left(\nu_L^A/\theta_L^A\right)\left(\varepsilon_D^A - 1\right)/\left(\varepsilon_D^A + \varepsilon_S^A\right) \\ &+ (1-\gamma)\left(\nu_L^R/\theta_L^R\right)\left(-\varepsilon_S^A - 1\right)/\left(\varepsilon_D^A + \varepsilon_S^A\right)\Big] t^A, \end{aligned} \qquad \textbf{[S19]}$$

which is the same as Eq. **S13**, 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 use the same techniques for evaluating the sign of the right side of Eq. **S19** as for global land use change.

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 condition 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 Eq. **3**. Now a productivity improvement in region A results in a rise in global emissions if

$$\varepsilon_D^W > (\alpha/\gamma)\left(\varepsilon_S^W + 1\right) - \varepsilon_S^W \Rightarrow e^W/t^A > 0, \qquad \textbf{[S20]}$$

where α/γ is the relative emissions efficiency of region A. Combining insights from the foregoing analysis, we find that 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 (*i*) global food demand is relatively elastic, (*ii*) the innovating region represents a large share of historical emissions from land use change, (*iii*) the innovating region has a low relative emissions efficiency, (*iv*) the extensive margin of supply response in the innovating region is large relative to the rest of the world, and (*v*) the intensive margin of supply response in the rest of the world is relatively large.

Numerical Values Associated with the Two-Region Theoretical Model. In the text we discuss the numerical values for key parameters in the theoretical model, which we use to evaluate Eq. **2**. These numerical values are obtained by aggregating the 2006 benchmark SIMPLE model to two regions. This aggregation groups together the historical Green Revolution regions: Asia, Latin America, and the Middle East, leaving all other regions in the RoW, and the Green Revolution region corresponds to sub-Saharan Africa (Table S5). Because the latter is a much smaller region, as shown by its 9% crop production share and 13% cropland share, we observe a much larger excess demand elasticity. Also notable is the relatively high cropland supply elasticity in Africa. All of these entries are computed under the assumption of fully integrated crop markets. However, as we have seen above, markets have historically been segmented. To shed light on the segmented markets case, we also compute the excess demand elasticity facing each region in the case of segmented markets. These values are reported in the parenthetic entries of Table S5.

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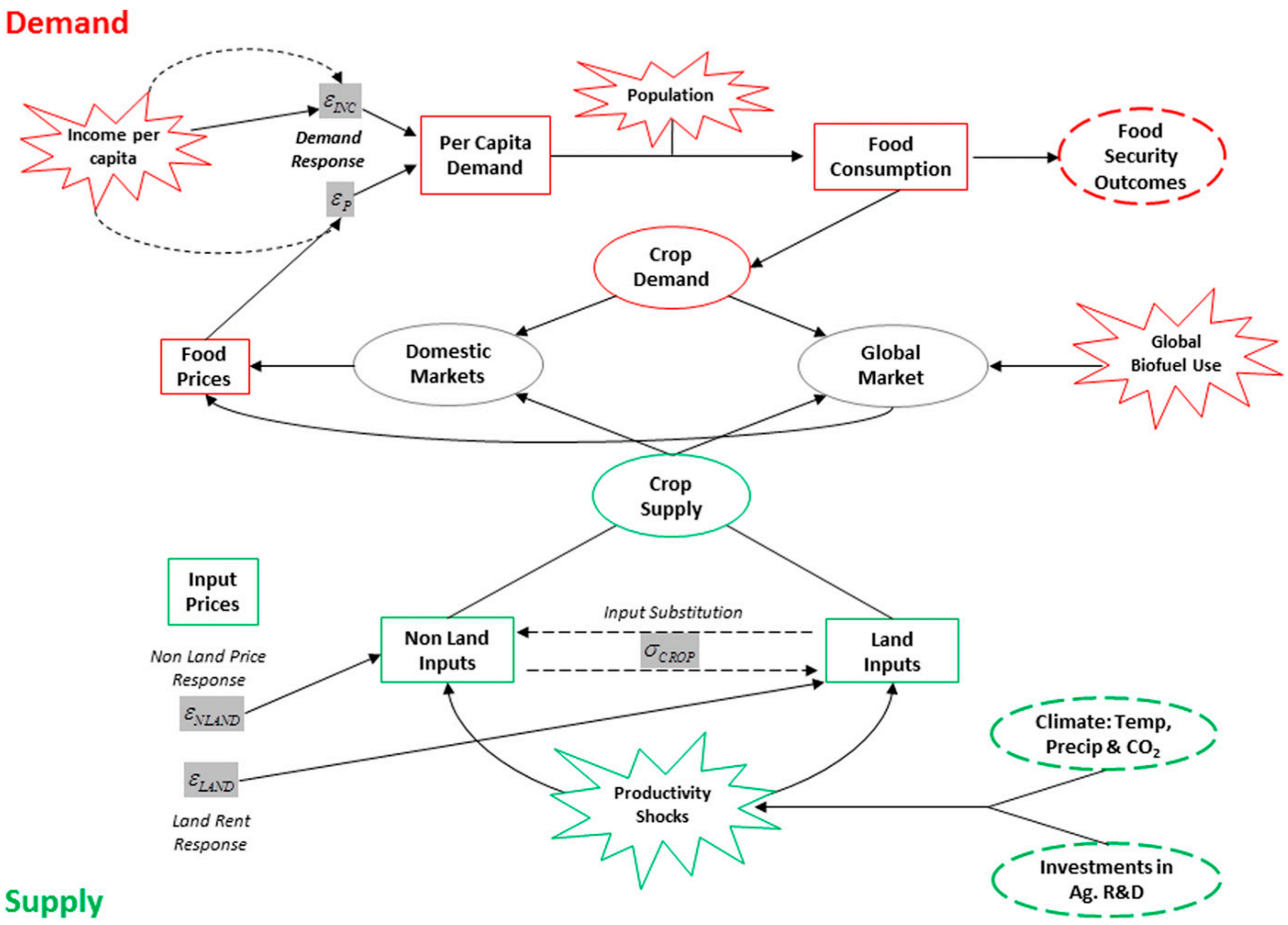

Fig. S1. Diagram of the SIMPLE model. (*Lower*; green) Regional crop production for the aggregate crop commodity. (*Upper*; red) Regional crop demand. The disposition of crops includes direct consumption, feedstuff use and food processing, and biofuels. Under market segmentation, consumers and producers interact in the domestic and international crop markets.

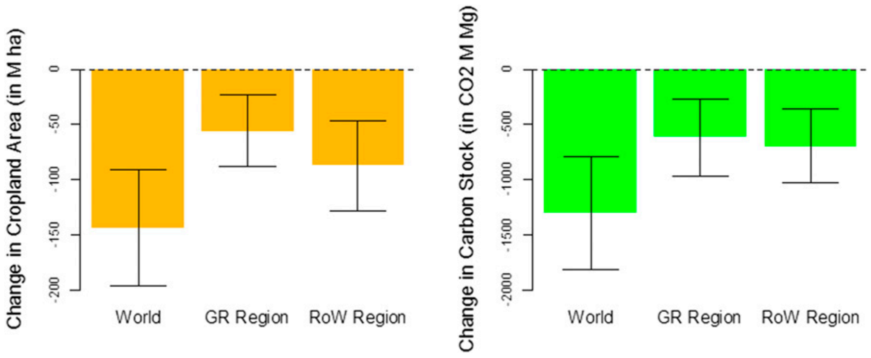

Fig. S2. Sensitivity analysis of the regional and global cropland and CO_2 emissions change under the historical simulation: difference between with vs. without historical Green Revolution TFP growth under market segmentation. Error bars reflect 95% CIs obtained from Monte Carlo analysis with respect to parameter uncertainty.

Table S1. Triangular distributions of selected parameters

Global parameters	Parameter	Mode	Maximum	Minimum
Demand elasticities				
Income elasticities: regression intercept	EIY			
Crops		0.88	1.15	0.62
Livestock		1.05	1.36	0.73
Processed foods		1.20	1.56	0.84
Price elasticities: regression intercept	EIP			
Crops		−0.74	−0.52	−0.96
Livestock		−0.83	−0.58	−1.07
Processed foods		−1.17	−0.82	−1.52
Nonland supply response	ENLAND	1.34	1.74	0.94
Land supply response	ELAND	0.28	0.36	0.20
Elasticity of substitution: crop	ECROP			
Historical simulation		1.13	1.47	0.79
Future projection		3.00	3.90	2.10
Elasticity of substitution: livestock	ECRPFEED	1.16	1.51	0.81
Armington elasticities	ESUB	2.50	5.00	1.25
Carbon loss per area of cropland (in CO_2 Mg/1,000 ha)	C_EMIS_HA	−6,310	−4,418	−8,202

Table S2. Regional scalars for selected parameters

Regions	Land supply response	Carbon loss per hectare of cropland
Eastern Europe	2.00	0.69
North Africa	0.39	0.16
Sub Saharan Africa	2.00	2.81
South America	2.00	3.22
Australia/New Zealand	2.00	0.54
European Union+	0.39	0.79
South Asia	1.00	0.52
Central America	1.00	2.65
Southern Africa	1.00	1.43
Southeast Asia	1.00	4.27
Canada/US	1.00	1.00
China/Mongolia	1.00	1.49
Middle East	0.39	0.45
Japan/Korea	0.39	2.35
Central Asia	2.00	0.92

Table S3. Key growth rates for the historical and future simulations

Regions	Population	Per capita income	Biofuels	Total factor productivity			Yield growth from Green Revolution
				Crops	Livestock	Processed food	
Eastern Europe	−0.36 [0.60]	4.75 [0.57]		[0.83]	1.04		
North Africa	1.02 [2.14]	3.49 [2.38]		[1.94]	−0.30		[0.69]
Sub Saharan Africa	2.44 [2.75]	3.80 [0.46]		[0.78]	0.42		0.88
South America	0.67 [2.05]	2.61 [1.62]		[1.74]	2.64		[0.66]
Australia/New Zealand	1.04 [1.54]	1.62 [2.11]		[1.44]	0.42		
European Union+	0.11 [0.48]	1.34 [2.56]		[2.10]	0.50		
South Asia	0.83 [2.14]	4.97 [2.62]		[1.16]	1.71		[0.88]
Central America	0.84 [2.27]	2.40 [1.97]		[1.17]	2.64		[0.66]
Southern Africa	0.64 [2.27]	2.62 [1.07]		[1.69]	0.42		0.88
Southeast Asia	0.79 [2.18]	3.67 [3.34]		[1.62]	2.38		[0.88]
Canada/US	0.66 [1.06]	1.01 [2.31]		[1.65]	0.42		
China/Mongolia	0.10 [1.56]	5.90 [7.03]		[2.01]	2.38		[0.88]
Middle East	1.21 [2.24]	1.01 [2.61]		[1.42]	−0.25		[0.69]
Japan/Korea	−0.20 [0.85]	1.96 [3.59]		[2.18]	0.42		[0.88]
Central Asia	0.96 [0.60]	4.90 [0.57]		[0.83]	1.04		
World			5.75	0.94	[1.30]	0.89 [0.89]	

Rates within brackets are for the historical period (1961–2006), whereas the rest are for the future period (2006–2051). Data sources from left to right: UN World Population Prospects (1), future and historical income growth rates from Fouré et al. (2) and WDI (3), respectively, biofuels from IEA (4, 5), future and historical growth rates of crop TFP from Ludena et al. (6) and Fuglie (7), respectively, and future TFP growth rates for crops, livestock, and processed foods from Ludena et al. (6), Griffith et al. (8), and Evenson (9).

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Table S4. Summary of terms used in the theoretical analysis

Parameters	Description
t : Total factor productivity	Ratio of output to inputs used in crop production, accounting for both land and nonland inputs
ε_D : Price elasticity of crop demand (Demand margin)	Percent change in crop consumption given a one percent change in crop price
ε_S : Supply elasticity of crops	Percent change in crop production given a one percent change in crop price
ν_L : Supply elasticity of cropland	Percent change in cropland area supplied to the crop sector given a one percent change in cropland returns
ν_L/θ_L : Extensive margin of supply	The potential for cropland expansion in response to higher crop prices
σ : Elasticity of substitution	Scope for input substitution between land and nonland inputs used in crop production
$\sigma[(1/\theta_L)-1]$: Intensive margin of supply	The potential for crop yield increases in response to higher crop prices
$[\varepsilon_D+(1-\alpha)\varepsilon_S]/\alpha$: Excess demand elasticity	Price responsiveness of demand for regional crop output, once RoW supply response is factored in

Table S5. Key parameters corresponding to the analytical model based on two alternative two region aggregations

Region	Production share	Cropland share	Cropland supply elasticity	Total supply	Excess demand elasticity	Relative yield	Relative emissions efficiency
Historical Green Revolution							
RoW region	0.34	0.53	0.49	1.08	2.82 (0.78)	0.64	1.05
Asia-Latin America-Middle East Green Revolution region	0.66	0.47	0.38	1.03	0.98 (0.50)	1.40	0.96
World	1.00	1.00	0.44	1.05	0.28 (0.29)	1.00	1.00
African Green Revolution							
RoW region	0.91	0.87	0.41	1.03	0.43 (0.31)	1.05	1.15
African Green Revolution region	0.09	0.13	0.64	1.25	13.53 (0.74)	0.69	0.50
World	1.00	1.00	0.44	1.05	0.28 (0.29)	1.00	1.00

Parameters correspond to the definitions in the theoretical model underpinning in Eqs. **1–3**. The parameters have been computed based on the 2006 database for SIMPLE and associated model parameters, aggregated from 15 regions to the two different groupings of two regions shown here. The historical Green Revolution comprises Asia, Latin America, and the Middle East, whereas the African Green Revolution refers to sub-Sahara Africa. In both cases, RoW refers to the grouping of all remaining regions in the model. The parenthetic entries in this table refer to the values of the excess demand elasticities facing each region in the presence of segmented markets.