Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO₂ emissions

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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 the assertion that agricultural innovation is land sparing. However, numerous case studies and global empirical studies have found little evidence of higher yields being accompanied by reduced area. We find that these studies overlook two crucial factors: estimation of a true counterfactual scenario and a tendency to adopt a regional, rather than a global, perspective. This paper introduces a general framework for analyzing the impacts of regional and global innovation on long run crop output, prices, land rents, land use, and associated CO₂ emissions. In so doing, it facilitates a reconciliation of the apparently conflicting views of the impacts of agricultural productivity growth on global land use and environmental quality. Our historical analysis demonstrates that the Green Revolution in Asia, Latin America, and the Middle East was unambiguously land and emissions sparing, compared with a counterfactual world without these innovations. In contrast, we find that the environmental impacts of a prospective African Green Revolution are potentially ambiguous. We trace these divergent outcomes to relative differences between the innovating region and the rest of the world in yields, emissions efficiencies, cropland supply response, and intensification potential. Globalization of agriculture raises the potential for adverse environmental consequences. However, if sustained for several decades, an African Green Revolution will eventually become land sparing.

Significance

Agriculture is a key driver of tropical deforestation, and there is heated debate about whether productivity-enhancing crop innovations can slow such environmental degradation. For fixed food demand, globally higher yields will reduce cropland and hence deforestation. However, regional innovations often boost agricultural profitability and lower prices, thereby leading to cropland expansion in the innovating region. This paper develops a framework for understanding the impact of regional innovations on global land use and the environment. Although the historical Green Revolution in Asia, Latin America, and the Middle East is shown to have been land sparing, a future Green Revolution in Africa could lead to global cropland expansion in the context of a more fully integrated global agricultural economy.


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supply (QSW) and world demand (QDW) curves. The world supply is determined in the world market by the intersection of the world supply curve and the world demand curve. In so doing, it produces a general framework for analyzing the impacts of regional innovations on land use, global CO2 emissions, and environmental quality.

The literature evaluating the Borlaug hypothesis suffers from two major problems. First, the statistical studies suffer from the challenge of estimating what would have happened in the absence of such agricultural innovation (i.e., they are unable to account for the counterfactual world in their analysis). Second, there is a strong tendency in this literature to focus on particular regions of the world (5, 22, 23), thereby ignoring impacts of regional innovations on land use and CO2 emissions in the rest of the world, where these may fall. Accordingly, this paper introduces a general framework for analyzing the impacts of regional and global innovations on long run agricultural output, prices, land rents, land use, and associated CO2 emissions. In so doing, it facilitates a reconciliation of the apparently conflicting views of the impacts of agricultural productivity growth on land use, global CO2 emissions, and environmental quality.

Fig. 1 provides an overview of key elements of the land-sparing debate. The top left panel presents a supply and demand diagram explaining the equilibrium output and price in the innovating region (region A) before and after introduction of an improved agricultural technology (12, 24), which increases yields and shifts the region’s supply curve (QSA) to the right (to QSA*). Price is determined in the world market by the intersection of the world supply curve (QSW) and world demand (QDW) curves. The world supply curve represents the horizontal summation of supplies in both region A and the rest of the world (RoW), represented by the right panel. From this diagram, it is clear that the innovation in region A will result in a lower world price (PW falls to PW*) and hence a reduction in RoW output and land use. It is this land-sparing impact of region A’s innovation in RoW that is often ignored in the case study-based literature (5). The impact of the innovation on land use in region A is ambiguous, because it is the net outcome of two competing forces. On the one hand, improved technology means fewer inputs are required to produce the same level of output. However, improved technology also lowers costs and induces an expansion in equilibrium output, as shown in the top leftmost portion of Fig. 1. Not only is the impact on land use in region A ambiguous, this regional ambiguity is inherited by the global change in land use, as will be shown later in our analytical solution of this model.

Although the foregoing analysis appears straightforward, it is hardly this simple in practice, because supply in region A is not the only thing that is changing. Consider, for example, the historical period analyzed by Rudel et al. (19). During this period, global food demand was growing strongly due to the combination of population and income growth. This growth translated into an outward shift in global demand (QDW to QDW*) in Fig. 1, Lower). There was also technological progress in crop production in nearly every region of the world (25). These innovations are represented by the outward shifts in supply in both region A and in RoW, resulting in the global price reduction shown in Fig. 1, Lower. Given the multiplicity of factors at work here, it is difficult to know what would have happened if technological progress in region A had not occurred or if it had been slower. For this, we need a formal model. Accordingly, we use the Simplified International Model of Prices Landuse and the Environment (SIMPLE) model of global agricultural land use (SI Text and Fig. S1) (26) to reexamine the historical record considered by Rudel et al. (19) and Ewers et al. (21), as well as to explore future Green Revolution scenarios. Importantly, this version of SIMPLE has been modified to allow for the segmentation of regional markets (Fig. S1), a point to which we will return below.

Results

The Historical Green Revolution Was Indeed Land and CO2 Emissions Sparing Compared with a Counterfactual World Without These Agricultural Innovations. There was a remarkable increase (>200%) in global crop production over the 1961–2006 period as a result of the Green Revolution (Fig. 2, Upper, blue bars for observed global values). Most of this output expansion was achieved through higher yields, especially in regions that experienced the Green Revolution. The expansion in cropland area was just 11%, and real crop prices fell by 29% over this historical period. The other
important point to note is that both yields and area expanded in the Green Revolution region, whereas in the RoW, aggregate yields expanded and area remained essentially unchanged (Fig. 2: Lower, blue bars for observed regional values). These results are broadly consistent with the observation of Rudel et al. (19), who concluded that “rising yields and declining cultivated areas, does not generally characterize the results of historical total factor productivity (TFP, the ratio of an output index to an index of land and nonland inputs) measure used in this model (27). However, overall, this model with segmented regional markets performs better over this historical period than the previous version which assumed integrated world markets (26).

With this historical baseline simulation in hand, we are now in a position to explore a counterfactual scenario that we dub the no Green Revolution (no-GR) scenario. In this case, technological progress in Asia, Latin America, and the Middle East is slower due to the absence of improved germplasm. Rather than crop TFP growing at an annual average rate of 1.6% in Asia and Latin America, it grows at just 0.5% in our counterfactual (12, 28). By subtracting the results of our counterfactual no-GR scenario (red bar in each group of Fig. 2) from the GR scenario (green bars), we obtain a model-based assessment of the impact of the Green Revolution on cropland use, yields, output, and global price over this historical period.

Results in Fig. 2 show that the Green Revolution causes land area in the affected region to be smaller than it would have been without the Green Revolution (26% with GR and 37% without GR). The growth in global output is also notably greater in the case of the Green Revolution. Rather than a reduction in global crop prices as observed in the historical GR baseline, the model simulates a 30% price increase over the 1961–2006 period under the no-GR counterfactual. RoW cropland use is much lower under the GR scenario (~2% with GR and ~9% without); hence, we see from Fig. 2 (Upper) that the Green Revolution was indeed land sparing at the global scale compared with the no-GR counterfactual (11% global cropland increase with GR and 21% without GR). Furthermore, the error bars reported in Fig. S2 show that these land use deviations from baseline in the GR region, the RoW, and worldwide are all robust to variation in the SIMPLE model parameters (Tables S1 and S2).

We can also assess the impact of the GR on CO2 emissions from land cover change. To do so, we multiply the land cover change predicted by SIMPLE by carbon emission factors per hectare estimated using yield and carbon loss estimates from West et al. (29) (SI Text). [Note that unlike Burney et al. (17), here we are only considering CO2 emissions from land cover change, neglecting emissions from intensification, e.g., N2O from fertilizer use. Burney et al. (17) found that differences in CO2 emissions dominate the overall effect on greenhouse gases.] These results are also reported in Fig. S2 and show robust evidence of global CO2 savings from the GR, with a mean reduction of ~1,300 MMg. Both of these findings are consistent with the recent work of Stevenson et al. (12), who analyzed this question in the context of their comparative static simulation of a disaggregated global economic model of agriculture.

![Fig. 3. Sensitivity analysis of the regional and global cropland change and their corresponding carbon emissions given a future African Green Revolution under both segmented and integrated markets: difference between with vs. without Green Revolution TFP growth. Error bars reflect 95% CIs obtained from Monte Carlo analysis with respect to parameter uncertainty.](image-url)
international markets better approximates what was observed over the 1961–2006 period (26). However, the world economy is changing rapidly. One of the primary objectives of the Uruguay Round Agreement, which resulted in formation of the World Trade Organization in 1994, was to bring greater discipline to international agricultural trade and there is evidence that distortions to agricultural trade are being dismantled (33). Therefore, it is of great interest to examine how these findings might be altered in the context of a more fully integrated global economy.

After appropriate condensation of the demand side, adding the assumption of fully integrated world markets and modest simplification of the supply side, the SIMPLE model can be condensed and solved analytically (SI Text and Table S4). In particular, we aggregate across all of the sources of crop demand, including biofuels, as well as direct consumption, input demands in livestock, and crop use in processed foods in each of the 15 model regions. This aggregation has no effect on model behavior and simply results in a single, global demand schedule, as shown in Fig. 1 (middle graph). On the supply side, we aggregate across countries within the GR and no-GR regions. The theoretical model also assumes that the price of nonland inputs is unaffected by the innovation (This assumption tends to exaggerate the potential for endogenous intensification.) With these simplifications, we can now obtain a general theoretical solution to the model expressed in terms of percentage changes in equilibrium prices and quantities as a function of the change in crop TFP (SI Text). The analytical model offers the following insights into the land-sparing nature of agricultural innovations.

Global TFP Growth in Agriculture Will Increase Land Use and CO2 Emissions if and Only if the World Demand for Crops Responds Strongly to Changes in Price. If we start by postulating a common rate of technological change worldwide (superscript W denotes global variables), then the percentage change in worldwide land use \( q^W \) given a 1% change in global TFP \( \ell^W \) is given by the following expression (see Table S4 for a full discussion of the terms in this expression):

\[
\frac{q^W}{q^W} = \left( \frac{\ell^W - 1}{\ell^W} \right) \left\{ 1 + \sigma^W \left[ \left( \ell^W \theta^W \right) - 1 \right] - \left( V^W / \ell^W \right) \right\}.
\]

where \( \sigma^W > 0 \) is the absolute value of the global price elasticity of demand for crops. We refer to this as the demand margin of price response. This unit-less measure describes the slope of the world demand schedule in Fig. 1, reporting the percentage change in global demand in response to a 1% change in price (Table S4). If it is greater than one, then demand is termed price elastic as the quantity response is larger than the price change (in percentage terms). The global price elasticity of demand depends on the responsiveness of both consumer demands and livestock and food processing demands for crops. The term \( \sigma^W \left[ \left( \ell^W \theta^W \right) - 1 \right] \) captures the potential for yield increases in response to higher crop prices (the intensive margin of supply response), whereas the parameter \( \sigma^W \) describes the potential for substituting non-land for land in crop production (elasticity of substitution) and \( \theta^W < 1 \) is the share of land in global production costs. The term \( \left( V^W / \ell^W \right) \) reflects the potential for cropland expansion given increases in crop prices (the extensive margin of supply response), where \( V^W \) is the global supply elasticity of cropland. This term represents the percentage change in global cropland supply in response to a one percent change in cropland returns.

Eq. 1 confirms that TFP growth will cause land to expand if and only if world demand for crops is price elastic \( \sigma^W > 1 \). This point is well understood in the literature (5); however, our analytical expression offers additional insights. In particular, the magnitude of any expansion or contraction will depend on the cropland area response, the importance of land in total costs, and the potential for substitution of nonland inputs for land. We can say unambiguously that the larger the elasticity of substitution in production \( \sigma^W \), the more muted will be the global cropland area response to TFP growth. For large values of the intensification parameter relative to the price elasticity of demand (i.e., \( \sigma^W > \ell^W \)), so the third term in the denominator is negligible relative to the second, we have the additional result that the land area response to TFP is diminished when the cost share of land in total crop production rises. Finally, note that the denominator in this expression hinges on the relative sizes of the intensive/extensive margins \( \{\ell^W (1/\theta^W) - 1\} / \theta^W \) and the demand/extensive margins \( \left( V^W / \ell^W \theta^W \right) \).

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come from having a small share of global production: \( \alpha \to 0 \), region A simultaneously comprises a relatively large share of global cropland 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 cropland supply response is relatively large, i.e., \( \mu W L ^ 2 / C_0 \gg \mu W L / C_0 \), Jevon’s paradox also becomes more likely. Finally, a larger intensive margin in RoW results in a greater contraction of output in that region and therefore more scope for the low-yielding innovating region to expand its area. However, it is not possible to say anything more precise about the conditions for global area expansion or contraction in this general case (SI Text).

Special cases yield more clear-cut predictions (SI Text). One that is particularly useful to discuss here is the case when both regions have the same supply response. Now the condition for Jevons’ paradox simplifies to

\[
es D W > (Y^W Y^W) (\varepsilon S W + 1) - \varepsilon W \Rightarrow (d L / d t) > 0, \tag{3}
\]

where \( (Y^W Y^W) \) is the ratio of yields in region A to global yields. Therefore, 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. The logic is as follows: (i) agricultural area in region RoW falls in the wake of the productivity improvement in A; (ii) the RoW area displaced by increased production in A will be smaller, and thus the smaller is this yield ratio (smaller right side in Eq. 3); and finally (iii) the larger the increase in global demand due to the resultant price decline (larger left side in Eq. 3), the greater the overall increase in global output that needs to be supported.

We can use this framework to shed further insight into the land-sparing nature of the Green Revolution. Table S5 summarizes the parameters underpinning Eq. 2 in the year 2006, aggregated from the 15 regions in SIMPLE to the level of the historical Green Revolution region and RoW. Relative yields in the historical GR region were 40% above the world average in 2006. Based on Eq. 3, this mitigates against Jevons’ paradox. Cropland area response is only about 80% of the world average, increasing the likelihood of TFP growth being land-sparing, based on Eq. 2. The excess demand elasticity (0.98) is also relatively low, again mitigating against Jevons’ paradox based on Eq. 1. Thus, it is no surprise that when we plug the aggregated parameters in Table S5 into Eq. 2, we find that \( d L / d t = -0.26 < 0 \), and this single-equation prediction provides the same land-sparing result obtained from simulation of the full SIMPLE model albeit in the context of segmented markets.

In the Context of Integrated World Markets, an African Green Revolution Will Only Be Land Sparing if It Is Sustained over Several Decades. The second set of parameters reported in Table S5 sheds light on potential impacts of an African Green Revolution in the context of fully integrated world markets. In particular, compared with the historical Green Revolution region, sub-Saharan Africa covers a smaller share of global cropland area (13%) but has a much stronger cropland area response to price (0.64 vs. 0.44 for the world) and exhibits yield and emissions efficiencies that are relatively low (just 69% and 50% of the global average, respectively). In light of Eq. 2, these factors suggest that an African Green Revolution has the potential to exhibit Jevons’ paradox. Indeed, if we plug the parameters from Table S5 into Eq. 2, we find that \( d L / d t = 0.02 > 0 \), which suggests that the African Green Revolution would be not land sparing if implemented in 2006 in the presence of fully integrated world markets. We can also see from Eq. 2 why the African GR is land sparing in the presence of segmented markets. For Africa, the excess demand elasticity is \( \leq 1 \) (0.74; see parenthetical entries in Table S5), thereby suggesting a land-sparing outcome when evaluated using Eq. 2, because both terms on the right side become negative in this case.

At this point in the theoretical analysis, we must introduce an additional complication: the fact that the parameters reported in Eq. 2 are in fact variables that will change as a result of economic growth, as well as a potential Green Revolution. The most obvious instance is that of relative yields. We expect this ratio to rise in the wake of an African GR. Indeed, we can use Eq. 2 to calculate the critical point at which (holding other variables constant) further productivity growth in the region would boost the yield ratio sufficiently to eventually change the sign in this expression. We find that the critical value for the yield ratio is 0.86, which would be achieved after \( \sim 20 \) y of GR-induced productivity growth.

We can also return at this point to the SIMPLE model, only now assuming fully integrated world markets. As before, we start from the 2006 base and project the global economy forward, first under the baseline assumptions and subsequently assuming that the African GR commences in 2025 and persists through 2050. Results are reported in the right panel of Fig. 3. As anticipated by our theoretical model, the impact on global land use is ambiguous. However, given the insights offered by Eq. 3 and the preceding discussion, it is clear that the longer this GR persists, the more likely it is to become cumulatively land-sparing.

In the Context of a Fully Integrated Agricultural Economy, the African Green Revolution Is Likely to Increase CO2 Emissions from Cropland Cover Expansion. Within the analytical framework laid out above, it is also possible to derive conditions analogous to Eqs. 1–3 that bear on the question of global CO2 emissions from land conversion (SI Text). Indeed, the only difference is that, rather than relative yields driving the result (Eq. 3), the key metric is the emissions efficiency of region A, relative to the global value. Emissions efficiency refers to the yield per hectare of increased cropland, relative to the one-time carbon emissions associated with bringing that land into crop production. If this ratio is large in absolute value, then we say that the region has a high emissions efficiency. West et al. (29) computed these emissions efficiencies for a global grid and found that they are three times lower in the tropics compared with the temperate regions and are particularly low in sub-Saharan Africa. Indeed, the emissions efficiency in the sub-Saharan African region is just half of the world average (Table S5). This finding naturally raises a concern about whether an African Green Revolution would increase CO2 emissions. Because the remaining terms in Eqs. 1–3 are identical for the change in global emissions, we are left with a strong suspicion that this may indeed be the case.

The lower right panel in Fig. 3 reports the SIMPLE model simulated change in global CO2 emissions owing to the African Green Revolution, in the presence of fully integrated world markets. From these results, the prospective African Green Revolution boosts CO2 emissions in that region by enough to dominate the decline in RoW emissions from land use change. The error bars show this result to be robust to parameter uncertainty.

Discussion

The literature on the land use implications of technological change in agriculture has suffered from the absence of a unifying analytical framework and the associated absence of counterfactual scenarios in many studies. As with earlier studies (19), we verify that, indeed, over the 1961–2006 period, increasing yields were accompanied by increased cropland area in Green Revolution-affected regions. At first glance, this appears to be a refutation of the Borlaug hypothesis and an affirmation of Jevon’s paradox. However, once we consider the counterfactual scenario in which agricultural productivity in developing countries grew more slowly, due to the absence of the Green Revolution, we find more global land conversion relative to the real world case and not less. In other words, the historical Green Revolution did indeed spare land over this period compared with the counterfactual. Nonetheless, even in the counterfactual scenario, with slower productivity growth in the region no longer benefitting from the Green
Revolution, cropland area and yields still both rise over the historical period. These results clearly demonstrate the fallacy in simply examining correlations between historical yield and area changes in the absence of a proper counterfactual.

When our framework is used to analyze the impacts of a prospective African Green Revolution, we find that, provided global crop markets remain segmented as they have been historically, this would also be land and emissions sparing. However, in the context of integrated global markets, we show that innovations will most likely fail to be land or emissions sparing when they occur in regions with relatively low yields, low emissions efficiencies, and high land supply elasticities. These conditions are precisely those that apply presently in sub-Saharan Africa. However, we do not take the “low yields” to imply that the world should refrain from investing in improved agricultural technology for Africa or that policies should limit the extent of market integration. To the contrary, any measures that boost relative yields in the region will eventually ensure that cropland area expansion in sub-Saharan Africa is also land sparing. In addition, measures to discourage conversion of carbon-rich ecosystems to low-yielding crop production will help to boost environmental efficiencies in the region, thereby ensuring that future land use change does not increase global CO2 emissions.

Materials and Methods

In this paper, we use the SIMPLE model (26) (SI Text) to simulate cropland change over the historical period from 1961 to 2006. The 15 regions (Table S3) are aggregated into two regions for reporting: Green Revolution and Rest of the World (RoW). Each of the 15 regions consumes crops, livestock products, and other processed foods, with the demand characteristics varying by product and also by per capita income in the region. Crop production is based on the combination of land and nonland inputs in variable proportions. By increasing the intensity of nonland inputs per hectare, yields can be increased, given sufficient economic incentive. Production can also be expanded at the extensive margin by converting more cropland. The model is simulated over the 1961–2006 historical period by specifying exogenous changes in population and per capita income by demand region, as well as changes in TFP in crops, livestock, and processed foods production. As in Fig. 1, long-run equilibrium is achieved when global crop supply equals demand, subject to the segmentation of regional markets that limits the transmission of global market prices into the domestic economy and therefore reduces the excess demand elasticity facing the innovating region.

There are several important limitations of our methodology (SI Text). First is the assumption that the impact of technological change is limited to the innovating region. What if all crop innovations were perfectly transferable? In this circumstance, innovation in any region A is automatically transferred to RoW, which takes us back to Eq. 1 in which the impact of the innovation is felt globally and the condition for Jenov’s paradox is price elastic global demand—an unlikely condition, given the evidence on consumer demand (34). A second limitation is that the counterfactual we have constructed has been limited to modifying TFP growth. In reality, agricultural innovations may also have influenced population and income growth, which we have kept fixed in our model experiments. Nevertheless, we believe that the qualitative results and insights gained from this study are likely robust to alternate constructions of counterfactuals.

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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 average 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 regional-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 estimated parameters of Gurgel et al. (2) and Ahmed et al. (3). Nonland factors 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-saving 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 consumers 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 Arthington 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 Arthington 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 Arthington 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 CO₂ emissions, along with the error bars denoting the 95% CIs. From these results, it is clear that the historical GR was both a number of key parameters that will be important. These parameters are summarized in Table S4 for the sake of convenience.

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, −νν ≤ 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

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) qo = −ννpo</td>
<td>Demand for agricultural output</td>
</tr>
<tr>
<td>(2) ppo + t = ∑p j</td>
<td>Agricultural entry/exit; zero profits</td>
</tr>
<tr>
<td>(3) qj = qo − t − σ(pj − po − t)</td>
<td>Demand for agricultural inputs</td>
</tr>
<tr>
<td>∀j = 1 − N</td>
<td></td>
</tr>
<tr>
<td>(4) pj = 0, ∀j ≠ L</td>
<td>Supply of nonland inputs</td>
</tr>
<tr>
<td>(5) qj = σj pj, L</td>
<td>Supply of land to agriculture</td>
</tr>
</tbody>
</table>

Notation: All price and quantity variables represent percentage changes in the underlying indexes. qo, % change in long run agricultural output; qj, % 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; pj, % change in the price of agricultural input j; σ, ≥ 0, nonnegative elasticity of substitution between land and nonland inputs; νν ≥ 0, nonnegative price elasticity of demand for aggregate farm output; vj ≥ 0, nonnegative elasticity of land supply to agriculture; δj ≥ 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: ∑θθj.

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: σ(pj − 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: qfor − qo = σ(pfor − 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, νν 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

\[ p_L = \frac{\Theta_t}{\Theta_t} (p_0 + t). \]  

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

*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.
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 en-
suing 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
delicacy 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 pa-
rameters in the model as well as the productivity shock:

\[
p_L = t([s_D - 1]/[s_L + \sigma(\theta_L + t_L \theta_D)]) = \beta_L t. \tag{S2}
\]

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

\[
q_L = t(v_L \beta_L). \tag{S3}
\]

Substituting in the expression for \( \beta_L \) and rearranging, as well as
adding superscripts to denote the fact that we are considering a
worldwide change in technology, we obtain Eq. I. 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 \( \beta_L \) are nonnegative, \( t > 0 \Rightarrow p_L < 0 \) if, and
only if \( \epsilon_D < 1 \). That is, land supply and associated greenhouse
(gas) emissions will fall following a favorable technol-
ological 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 Angelsten and
Kaimowitz (15).

The farm level demand elasticity which is pertinent to Eq. I 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 rel-
evant 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 crop
land 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
(\( v_L \)) and the smaller the elasticity of substitution between land and
nonland inputs (\( \sigma \)). Eq. S2 can be rewritten in terms
of the implied commodity supply elasticity in this model,
\( \varepsilon_S = \theta_L \theta_U + \sigma(\theta_L^2 - 1) \), where the first term represents area
response to the commodity price change and the second re-
acts yield response to higher commodity prices. This substi-
utution results in Eq. S4

\[
p_L = t([s_D - 1]/[s_L + \sigma(1 - \theta_L + t_L \theta_D)]) = \beta_L t. \tag{S4}
\]

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

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

\[
po = -([s_D + 1]/[s_L + \sigma D])t = \beta_D t. \tag{S5}
\]

from which we see that favorable innovations will depress com-
modity price. The resulting equilibrium change in output can sim-
ply be read off the demand schedule

\[
qo = \epsilon_D \beta_D. \tag{S6}
\]

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
impact 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

\[
q^A = \epsilon^A_S p^A + \Delta^A_S, \quad q^R = \epsilon^R_S p^R, \quad \text{and} \quad q^W = \epsilon^W_S p^W. \tag{S7}
\]

Global market clearing requires that demand equals aggregated
regional supplies

\[
q^W = \alpha q^A + (1 - \alpha) q^R, \tag{S8}
\]

where \( \alpha = Q^A / Q^W \) 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

\[
po = -\alpha \Delta^A_S / (\epsilon^W_S + \epsilon^W_D) = \beta^W_S \epsilon^A. \tag{S9}
\]

Where the global supply elasticity is just the weighted combina-
tion of the regional supply elasticities: \( \epsilon^W_S = \alpha \epsilon^A_S + (1 - \alpha) \epsilon^R_S \).

We can now relate the two-region problem back to the single
region problem dealt with previously by rewriting Eq. S9 as fol-

\[
po = -\Delta^A_S / (\{[\epsilon^W_D + (1 - \alpha) \epsilon^R_D] / \alpha\} + \epsilon^A_S) = -\Delta^A_S / (\epsilon^A_D + \epsilon^A_S). \tag{S10}
\]

where \( \epsilon^W_D = [\epsilon^W_D + (1 - \alpha) \epsilon^R_D] / \alpha \) 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: \( \Delta q^L = (\varepsilon^L + 1)q^L \). Substituting this expression into Eq. S10 gives the following price impact owing to the technology shock:

\[
p_0 = -\left(\varepsilon^L + 1\right)q^L / (\varepsilon^L + \varepsilon^S) = \beta_0 q^t, \tag{S11}
\]

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:

\[
q^W_L = \delta q^L = (1 - \alpha)q^R + \delta (\varepsilon^L / \theta^L) (\beta_0 + 1)q^t + (1 - \delta) (\varepsilon^R / \theta^R) \beta_0 q^t, \tag{S12}
\]

where \( \delta = \frac{Q^L}{Q^W} \) 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: \( \alpha \theta > 0 \). 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:

\[
q^W_L / q^t = \left[ \frac{d(\varepsilon^L / \theta^L) (\varepsilon^D - 1) / (\varepsilon^D + \varepsilon^S)}{d(\varepsilon^R / \theta^R) (-\varepsilon^D - 1) / (\varepsilon^D + \varepsilon^S)} \right] + (1 - \delta) (\varepsilon^R / \theta^R) / (\varepsilon^L / \theta^L). \tag{S13}
\]

This 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 \( \alpha \theta > 0 \), 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: \( q^W_L / q^t > 0 \), 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, \( \varepsilon^L > 1 \). 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., \( \varepsilon^L \theta^L > \varepsilon^D \theta^D \), Jevon’s paradox becomes more likely. However, because these extensive margin supply elasticities also enter into the supply and excess demand elasticities in \( \beta_0 \), 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., \( \varepsilon^L \theta^L = (\varepsilon^R / \theta^R) = (\lambda/\theta_0) \). Therefore, the terms involving \( \delta(\lambda/\theta_0) \beta_0 q^t \) in Eq. S12 cancel and we are left with the following expression:

\[
q^W_L = (\delta + \beta_0)(\lambda/\theta_0) q^t. \tag{S14}
\]

Now the critical condition for Jevon’s paradox is \( \delta \geq 0 = \lambda \). This condition is most likely to arise when the affected region is large, \( \delta \to 1 \), and when excess demand is very elastic: \( \varepsilon^L > 0 \), 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 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 intensive and extensive margins.** To gain further insight into the conditions for global land area to decline, we can additionally assume that the extensive margin of supply response is identical in the two regions, so we may drop the regional subscripts in \( \sigma(\theta^{-1} - 1) \) as well, so that \( \varepsilon^L = \varepsilon^W = \varepsilon \). Now the expression for the incidence parameter, \( \beta_0 \), with the full excess demand expression substituted in, becomes

\[
\beta_0 = -\left[ \frac{\varepsilon^L + 1}{\frac{\varepsilon^W}{\alpha}} \right] \left( \frac{\varepsilon^W}{\alpha} + \frac{\varepsilon^D}{\alpha} \right) \tag{S15}
\]

The condition for Jevon’s paradox may therefore be written as \( \delta > \alpha \varepsilon^W / (\alpha \varepsilon^W + \varepsilon^S) \) or alternatively the following condition:

\[
\varepsilon^D > \alpha \delta \left( \frac{\varepsilon^W}{\alpha} + 1 \right) - \varepsilon^W = \left( q^W_L / q^t \right) > 0. \tag{S16}
\]

The ratio of the production share to the land share in Eq. S16, \( \alpha / \delta \), 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:

$$de^W = e^f dQ^A + e^R dQ^R_L.$$  \[S17\]

where $e^f$ 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 $Q^f_i/Q^f_I$, and dividing through by historical emissions, defined as $E^W = e^f A^R Q^f_I + e^R Q^R_I$, we obtain the following expression for the change in emissions, as a percentage of historical land-based emissions:

$$e^W = \left[\left(\frac{\gamma}{\theta^f} + 1\right)\left(\frac{\theta^f}{\theta^R} e^f - 1\right)/\left(\theta^A e^f + \theta^S\right)\right] r^d,$$  \[S18\]

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

$$e^W > \left(\frac{\alpha}{\gamma}\right)\left(e^W + 1\right) - e^W \Rightarrow e^W / r^d > 0.$$  \[S20\]

where $\alpha/\gamma$ 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.

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\textsubscript{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

<table>
<thead>
<tr>
<th>Global parameters</th>
<th>Parameter</th>
<th>Mode</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand elasticities</td>
<td>EIY</td>
<td>0.88</td>
<td>1.15</td>
<td>0.62</td>
</tr>
<tr>
<td>Income elasticities: regression intercept</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>-0.74</td>
<td>-0.52</td>
<td>-0.96</td>
<td></td>
</tr>
<tr>
<td>Livestock</td>
<td>-0.83</td>
<td>-0.58</td>
<td>-1.07</td>
<td></td>
</tr>
<tr>
<td>Processed foods</td>
<td>-1.17</td>
<td>-0.82</td>
<td>-1.52</td>
<td></td>
</tr>
<tr>
<td>Price elasticities: regression intercept</td>
<td>EIP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>-0.74</td>
<td>-0.52</td>
<td>-0.96</td>
<td></td>
</tr>
<tr>
<td>Livestock</td>
<td>-0.83</td>
<td>-0.58</td>
<td>-1.07</td>
<td></td>
</tr>
<tr>
<td>Processed foods</td>
<td>-1.17</td>
<td>-0.82</td>
<td>-1.52</td>
<td></td>
</tr>
<tr>
<td>Nonland supply response</td>
<td>ENLAND</td>
<td>1.34</td>
<td>1.74</td>
<td>0.94</td>
</tr>
<tr>
<td>Land supply response</td>
<td>ELAND</td>
<td>0.28</td>
<td>0.36</td>
<td>0.20</td>
</tr>
<tr>
<td>Elasticity of substitution: crop</td>
<td>ECROP</td>
<td>1.13</td>
<td>1.47</td>
<td>0.79</td>
</tr>
<tr>
<td>Historical simulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Future projection</td>
<td>3.00</td>
<td>0.90</td>
<td>2.10</td>
<td></td>
</tr>
<tr>
<td>Elasticity of substitution: livestock</td>
<td>ECRPFEED</td>
<td>1.16</td>
<td>1.51</td>
<td>0.81</td>
</tr>
<tr>
<td>Armington elasticities</td>
<td>ESUB</td>
<td>2.50</td>
<td>5.00</td>
<td>1.25</td>
</tr>
<tr>
<td>Carbon loss per area of cropland (in CO₂ Mg/1,000 ha)</td>
<td>C_EMIS_HA</td>
<td>-6,310</td>
<td>-4,418</td>
<td>-8,202</td>
</tr>
</tbody>
</table>

Table S2. Regional scalars for selected parameters

<table>
<thead>
<tr>
<th>Regions</th>
<th>Land supply response</th>
<th>Carbon loss per hectare of cropland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Europe</td>
<td>2.00</td>
<td>0.69</td>
</tr>
<tr>
<td>North Africa</td>
<td>0.39</td>
<td>0.16</td>
</tr>
<tr>
<td>Sub Saharan Africa</td>
<td>2.00</td>
<td>2.81</td>
</tr>
<tr>
<td>South America</td>
<td>2.00</td>
<td>3.22</td>
</tr>
<tr>
<td>Australia/New Zealand</td>
<td>2.00</td>
<td>0.54</td>
</tr>
<tr>
<td>European Union+</td>
<td>0.39</td>
<td>0.79</td>
</tr>
<tr>
<td>South Asia</td>
<td>1.00</td>
<td>0.52</td>
</tr>
<tr>
<td>Central America</td>
<td>1.00</td>
<td>2.65</td>
</tr>
<tr>
<td>Southern Africa</td>
<td>1.00</td>
<td>1.43</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>1.00</td>
<td>4.27</td>
</tr>
<tr>
<td>Canada/US</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>China/Mongolia</td>
<td>1.00</td>
<td>1.49</td>
</tr>
<tr>
<td>Middle East</td>
<td>0.39</td>
<td>0.45</td>
</tr>
<tr>
<td>Japan/Korea</td>
<td>0.39</td>
<td>2.35</td>
</tr>
<tr>
<td>Central Asia</td>
<td>2.00</td>
<td>0.92</td>
</tr>
</tbody>
</table>
Table S3. Key growth rates for the historical and future simulations

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

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).

Table S4. Summary of terms used in the theoretical analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$ : Total factor productivity</td>
<td>Ratio of output to inputs used in crop production, accounting for both land and nonland inputs</td>
</tr>
<tr>
<td>$e_D$ : Price elasticity of crop demand (Demand margin)</td>
<td>Percent change in crop consumption given a one percent change in crop price</td>
</tr>
<tr>
<td>$e_S$ : Supply elasticity of crops</td>
<td>Percent change in crop production given a one percent change in crop price</td>
</tr>
<tr>
<td>$v_L$ : Supply elasticity of cropland</td>
<td>Percent change in cropland area supplied to the crop sector given a one percent change in cropland returns</td>
</tr>
<tr>
<td>$v_L / (1 - \alpha)$ : Extensive margin of supply</td>
<td>The potential for cropland expansion in response to higher crop prices</td>
</tr>
<tr>
<td>$\sigma$ : Elasticity of substitution</td>
<td>Scope for input substitution between land and nonland inputs used in crop production</td>
</tr>
<tr>
<td>$\sigma(1 - (1 - \alpha) e_S) / \alpha$ : Intensive margin of supply</td>
<td>The potential for crop yield increases in response to higher crop prices</td>
</tr>
<tr>
<td>$e_0 + (1 - \alpha) e_S / \alpha$ : Excess demand elasticity</td>
<td>Price responsiveness of demand for regional crop output, once RoW supply response is factored in</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Region</th>
<th>Production share</th>
<th>Cropland share</th>
<th>Cropland supply elasticity</th>
<th>Total supply</th>
<th>Excess demand elasticity</th>
<th>Relative yield</th>
<th>Relative emissions efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Green Revolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RoW region</td>
<td>0.34</td>
<td>0.53</td>
<td>0.49</td>
<td>1.08</td>
<td>2.82 (0.78)</td>
<td>0.64</td>
<td>1.05</td>
</tr>
<tr>
<td>Asia-Latin America-Middle East</td>
<td>0.66</td>
<td>0.47</td>
<td>0.38</td>
<td>1.03</td>
<td>0.98 (0.50)</td>
<td>1.40</td>
<td>0.96</td>
</tr>
<tr>
<td>World</td>
<td>1.00</td>
<td>1.00</td>
<td>0.44</td>
<td>1.05</td>
<td>0.28 (0.29)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>African Green Revolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RoW region</td>
<td>0.91</td>
<td>0.87</td>
<td>0.41</td>
<td>1.03</td>
<td>0.43 (0.31)</td>
<td>1.05</td>
<td>1.15</td>
</tr>
<tr>
<td>African Green Revolution region</td>
<td>0.09</td>
<td>0.13</td>
<td>0.64</td>
<td>1.25</td>
<td>13.53 (7.4)</td>
<td>0.69</td>
<td>0.50</td>
</tr>
<tr>
<td>World</td>
<td>1.00</td>
<td>1.00</td>
<td>0.44</td>
<td>1.05</td>
<td>0.28 (0.29)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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-Saharan 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.