SPECIAL FEATURE

Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production

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New estimates of the impacts of germplasm improvement in the major staple crops between 1965 and 2004 on global land-cover change are presented, based on simulations carried out using a global economic model (Global Trade Analysis Project Agro-Ecological Zone), a multicommodity, multiregional computable general equilibrium model linked to a global spatially explicit database on land use. We estimate the impact of removing the gains in cereal productivity attributed to the widespread adoption of improved varieties in developing countries. Here, several different effects—higher yields, lower prices, higher land rents, and trade effects—have been incorporated in a single model of the impact of Green Revolution research (and subsequent advances in yields from crop germplasm improvement) on land-cover change. Our results generally support the Borlaug hypothesis that increases in cereal yields as a result of widespread adoption of improved crop germplasm have saved natural ecosystems from being converted to agriculture. However, this relationship is complex, and the net effect is of a much smaller magnitude than Borlaug proposed. We estimate that the total crop area in 2004 would have been between 17.9 and 26.7 million hectares larger in a world that had not benefited from crop germplasm improvement since 1965. Of these hectares, 12.0–17.7 million would have been in developing countries, displacing pastures and resulting in an estimated 2 million hectares of additional deforestation. However, the negative impacts of higher food prices on poverty and hunger under this scenario would likely have dwarfed the welfare effects of agricultural expansion.

agricultural productivity | land-use change

The competition for global agricultural land and forest resources is high on the development agenda as a result of climate change, rising commodity prices, and rising land prices. Land cover change is the third most important human-induced cause of carbon emissions globally and the second most important in developing countries (1). In turn, agricultural expansion, especially commercial agriculture (2), is the single most important determinant of tropical deforestation. Between 1980 and 2000, 83% of all new agricultural land in the tropics came from either intact forests (55%) or disturbed forests (28%) (3).

Many have argued that agricultural research to increase yields is critical to saving the world's remaining forests and in doing so, limiting losses of biodiversity (4, 5) and greenhouse gas (GHG) emissions (6, 7). The theory is that technological change improves productivity on existing agricultural land and saves natural ecosystems (including forests) from being converted to agriculture. This is commonly known as the *Borlaug hypothesis* after Norman Borlaug, the "father of the Green Revolution," who claimed that the intensification of agriculture between 1950 and 2000, partly as a result of the technological change made possible by the Green Revolution, had saved hundreds of millions of hectares* from being brought into agricultural production (8).

However, the relationship between adoption of new technologies and land-use and land-cover change is complex. Increases in productivity from new agricultural technologies may increase the profitability of agriculture in comparison with alternative land uses (such as forest and pasture), thereby encouraging expansion of the agricultural land frontier. This is particularly the case for crops with an elastic demand (9). Where this kind of technological change takes place in forest-rich regions, there is the potential for it to contribute to deforestation, and several case studies in Angelsen and Kaimowitz (10) are examples of this kind of outcome.

CGIAR, a global agricultural research partnership, is a major source of improved technologies for food crops, including the crop germplasm technologies that spurred the Green Revolution. The impacts of CGIAR technologies on global agricultural productivity have been well documented (11). Conversely, impacts of the CGIAR system on the environment have received little attention. The land-use effects of technological change may represent the single most important source of environmental impacts of the work of CGIAR globally (12). Earlier studies have argued that CGIAR-led agricultural technologies have significantly reduced agricultural expansion (relative to the counterfactual in which the observed productivity gains had not taken place) and in doing so potentially saved forests (13, 14).

It is not possible to assess these relationships directly in empirical studies, because the counterfactual cannot be observed. Moreover, the pathways through which technological change has impacts on land-use change are manifested through markets for agricultural outputs and the factors of production. For these reasons, the impacts of technological change in agriculture can only be estimated through modeling.

Previous Studies

A simple identity, the global food equation (9), links global population (N), food consumption and production (q), land area (L), and agricultural yield (q/L), with demand on the left-hand side and supply on the right-hand side:

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*The quote from Borlaug is: "If the global cereal yields of 1950 still prevailed in 2000, we would have needed nearly 1.2 billion more hectares of the same quality, instead of the 660 million hectares used, to achieve 2000's global harvest." (ref. 8, p. 359). We actually think that the "more" in this sentence is a typographical error. Borlaug's argument fits better with a total area of cereals in 2000 of 1.2 billion in absence of observed yield increases. This suggests a land-saving effect of 560 million hectares (1,220 million ha – 660 million ha), rather than 1.2 billion additional hectares.

SUSTAINABILITY SCIENCE

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$$N \times (q/N) = (q/L) \times L. \quad [1]$$

If agricultural yields do not change but population increases, then more land is required to feed everyone at the same level. Rising per capita consumption would require even more land be brought under cultivation. The variables for this identity for cereals, which includes the world's major food staples, for the period of our analysis (1965–2004) are given in Table 1. During this period global population almost doubled, and yet average per capita consumption rose by more than 10%. The increase in cereal production to meet this increase in demand has overwhelmingly come from an increase in average cereal yields, which more than doubled over the period. Area harvested of cereals increased by less than 2%, and a significant share of this was through increasing cropping intensity in existing cultivated area.

Borlaug (8) argued that, in the absence of these large increases in cereal yields between the 1960s and 2000s, the area under cereals would have had to expand by a similar percentage to meet the increase in food consumption observed in the 2000s. The hypothesis is based on the relationship between production (supply) of a commodity and its world price, and how the price would affect farmers' land-use decisions. It suggests that without new agricultural technologies, productivity would remain stagnant, which would lead to increases in the price of food commodities on the world market. In response to higher prices, producers would expand production by cultivating more land. This argument is based on a number of assumptions. Most important of these is the assumption of no changes in demand as a result of changes in the increased food prices. In addition, there is also no possibility of a yield response to higher prices, no possibility of a localized land rent effect from productivity driving land-use/land-cover change, and no way of capturing the effects on factor substitution and economy-wide effects. As a result, the simple calculations such as those performed by Borlaug, and others since (13), tend to overestimate the extent of land-savings relative to a more realistic counterfactual; they represent the upper bound estimates of the true effect. The same logic has been used by Burney et al. (6) across all crops to estimate the impacts of agricultural intensification on GHG emissions. Their main result of 161 gigatons of carbon (GtC) emissions avoided since 1961 through agricultural intensification is based on the assumptions of the global food equation.

More realistic economic modeling approaches are needed to account for the various market effects of technological change. In the case of the CGIAR, Evenson and Rosegrant (14) conducted a comprehensive modeling analysis based on the findings of a major initiative that estimated the adoption and impact of crop germplasm improvement (CGI) across developing countries (15). They compared the observed level of crop technology in developing country agriculture in 2000 (referred to as the "base case") with a scenario in which there was no crop germplasm improvement since 1965. In this counterfactual scenario, developed countries still benefited from crop germplasm improvement consistent with their historical record for the period.

Table 1. Changes in the global food equation between 1965 and 2004 (3-y rolling averages, all data from FAOSTAT)

Parameter	1964–1966 (3-y average)	2003–2005 (3-y average)	% increase
Demand side			
Population (billions)	3.33	6.43	93
Food per capita (kg per capita per y)	311	344	10.6
Supply side			
Area harvested (million ha of cereals)	669	680	1.6
Cereals yield (Mt per ha per y)	1.53	3.25	112

Evenson and Rosegrant (14) used the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), a multimarket, multicountry model with 17 crop commodities and 35 countries or regions. In IMPACT, crop supply and demand factors determine the market-clearing prices, quantities supplied and consumed, and the trade volumes. Evenson and Rosegrant estimated that crop area in 2000 would have been 2.8–4.6% higher without crop germplasm improvement in developing countries than the actual case observed over the same period. Land-saving estimates were higher for rice (7.5–9.4%), one of the focus crops of the Green Revolution in Asia, than for other staple crops.

A range of 3–4% of agricultural land saved between 1965 and 2000 corresponded to 9–12 million ha in developed countries and 15–20 million ha in developing countries. These estimates of a total land-saving effect from crop germplasm improvement of 24–32 million ha between 1965 and 2000 are an order of magnitude lower than those based on the simplistic approach used by Borlaug but are still significant from the perspective of potentially averted deforestation, biodiversity loss, and GHG emissions.

However, there are many restrictive assumptions associated with the IMPACT model. First, IMPACT is only a partial equilibrium model for the agricultural sector—it does not compute equilibria for other markets, which misses an entire pathway of impacts via effects on nonfarm incomes and their feedback to the agricultural sector via product and factor markets (labor and capital). Second, the model does not include a land market and lacks any explicit link to the physical realm of existing land-cover. This means that one cannot estimate the "encroachment factor"—the extent to which the additional hectares required under lower-yielding technologies would have come from forest, rather than from grazing land or other land-cover with lower value to society than forests—and also where these changes are likely to have taken place. Using IMPACT, crop germplasm improvement can only save land because there is no mechanism for modeling land competition between crop and noncrop uses. Even among crops, the coverage is only partial.

For a more comprehensive analysis we use a global model that includes the land rent effects and impacts on land-use via factor markets. The Global Trade Analysis Project Agro-Ecological Zone (GTAP-AEZ) model is a multicommodity, multiregional computable general equilibrium model based on national or regional input–output tables. The crop coverage is complete in GTAP-AEZ, although crops are aggregated into only five categories, complicating the inclusion of specific CGIAR crops. Eighteen agroecological zones are defined, several of which may occur within a country.

In GTAP-AEZ the land rent effect is incorporated, which then allows us to model the net effect of land-saving minus increased expansion, while also modeling land supply through a constant elasticity of transformation between crop, pasture, and forest lands. GTAP-AEZ uses historical patterns of trade between pairs of countries—the Armington assumption (16)—in determining where expansion and contraction of agricultural area takes place.

As for Evenson and Rosegrant (14), our starting points are Evenson's (17) estimates of the annual changes (average 1960–1998) in total factor productivity (TFP) observed in cereals and other crops (Table S1). TFP is defined as the additional agricultural output resulting from crop germplasm improvement holding farm inputs constant. Because crop germplasm improvement interacts with other sources of productivity growth (such as extension programs and agronomic research), observed changes in TFP are inherently uncertain. Evenson (17) bounds this uncertainty by offering a lower and an upper estimate of TFP growth. His lower estimate of crop germplasm improvement ignores complementarities with other sources of productivity growth, whereas his upper estimate assumes positives complementarities between them. Fig. 1 shows the lower and upper

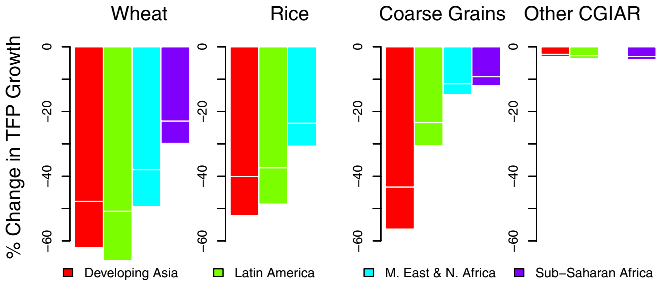

Fig. 1. Negative shocks to TFP growth in developing country agriculture during the period 1965–2004 equivalent to removing the observed productivity gains from crop germplasm improvement [estimated by Evenson (17), pp. 466–467]. The lower-bound TFP shocks are given by the segment between the origin and the white line. The additional segment represents the upper-bound TFP shocks.

TFP shocks compounded during the period 1961–2004 experienced by the cereals (wheat, rice, and coarse grains) and other crops (cassava, lentils, beans, and potatoes) in the developing world that benefited from CGI [*SI Materials and Methods* and Table S2 provide detailed mapping from original crops in Evenson and Rosegrant (14) to GTAP]. The more negative the productivity shock is, the greater the observed contribution from crop germplasm improvement is estimated to have been in this period. These negative TFP shocks to crop agriculture allow us to track the main price, production, land-use, trade, and emission effects in a counterfactual world that did not benefit from the observed productivity gains in agriculture attributable to crop germplasm improvement.

Results

Simulated changes (lower and upper estimates relative to the 2004 baseline) in production, prices, imports, and harvested area are shown in Fig. 2 for developed and developing regions as well as for the world (Table S3). Focusing first on the developing regions, in the absence of CGI, wheat production in 2004 would have been 43–60% lower than observed. Rice, coarse grains, and the other CGIAR crops affected by the productivity shocks also show reduced outputs. Oilseeds and the rest of the agricultural products, although not directly affected by the shocks, also show declines in production as a result of the reallocation of production factors (such as land) to those crops for which prices would have increased.

Fig. 2 (*Upper Middle*) shows that the output reductions in the developing world are ultimately reflected in increased regional and world prices. For instance, in the developing world, wheat prices would have more than doubled in the absence of CGI (121–272%). Fig. 2 (*Lower Middle*) shows that the reductions in wheat output in developing countries would have partially been offset by increases in imports, which also more than doubled in both scenarios. Such a surge in import demand drives wheat prices up in the developed world. Thus, using export values as weights, global weighted average wheat prices would have been 29–59% higher than they actually were in 2004. Similarly, global rice prices would have been 68–134% higher, reflecting the fact that rice is mostly produced in developing countries where we are applying the shocks. The coarse grains also show significant world price increases (20–41%), whereas changes in the world prices in the other CGIAR crops are more moderate (6–10%), reflecting both lower CGI gains in cassava and the fact that potatoes and cassava represent relatively low shares of the production value of the world agricultural sector. The price increases obtained by Evenson and Rosegrant (14) are remarkably similar to those reported here (Table S4). For the 1965 CGI counterfactual, Evenson and Rosegrant found that wheat prices increased by 29–61%, rice by 80–124%, maize by 23–45%, and other grains by 21–50%.

Fig. 2 shows that price effects are the consequence of reduced productivity, but at the same time higher prices make production more profitable, thus attracting production factors (land, labor, capital) that are withdrawn from other activities. Fig. 2 (*Bottom*) shows how the harvested area of rice and coarse grains increases considerably under the 1965 CGI counterfactual in both developing and developed regions. Table S5 has a further level of disaggregation of these results. The expansion of lands in these sectors is partly sustained by reductions of land in wheat in developing countries, and oilseeds and the rest of the agricultural sector in both developing and developed countries. The reduction in output is accompanied by displacement of production from the developing to the developed countries—the production of wheat and rice in developed countries expands significantly, driven entirely by area expansion of these crops. The overall result is a moderate reduction of total output ranging from 1.9% to 2.3% (last plot in Fig. 2, *Top*, shows changes for the agricultural sector as a whole) and an increase in harvested area ranging from 1.5% to 2.2%. This translates to an expansion in cropland of between 17.9 and 26.8 million ha (Fig. 3), which is comparable to the results of Evenson and Rosegrant (14), who estimated 24–32 million ha globally.

Additional crop land in GTAP-AEZ is obtained through conversion of pastures or forests. Fig. 3 shows that additional agricultural land would come mainly from pastures (15.6–24.8 Mha) and some from forests (approximately 2 Mha). In Figs. 4 and 5 we also show estimates of the GHG emissions implied by our counterfactuals. We include emissions from changes in fertilizer production (18), land cover change (19), agricultural soils (20), and rice cultivation (20), which range from 5.2 to 7.4 GtC equivalent (shown in Fig. 4). Fig. 5 shows negligible increases in emissions from changes in fertilizer production (consistent with the moderate output reductions discussed above), as well as very moderate increases in the emissions from agricultural soils and rice cultivation (consistent with a moderate expansion of the cropland). Therefore, almost all of the total increase in GHG emissions in the absence of crop germplasm improvement would come from changes in land cover.

These simulation results from GTAP-AEZ demonstrate that for the main staple food crops, there is a net land-saving as a result of global crop germplasm improvement in developing countries and associated increases in yields observed since 1965. These estimates are orders of magnitude lower than predicted by the simple global food equation that does not take account of feedback loops through prices of products, consumption demand, and land-use decisions. For example, Burney et al. (6) found that expansion of cropland would have been 864–1,514 Mha greater without agricultural intensification (lower bound: yields and fertilizers at 1961 levels and no increase in consumption; upper bound: yields and fertilizers at 1961 levels with real-world observed evolution in consumption), corresponding to 86.5–161 GtC higher emissions than observed. We should note that Burney et al. (6) subtract total yield growth globally to obtain their estimates, whereas the results reported here subtract only TFP growth in a limited number of crops in the developing countries, meaning that the results are not directly comparable.

The lower net land-saving effects reported here still represent a significant positive impact of agricultural research on the environment. However, the overall effects on land-saving are dwarfed by the effects of crop germplasm improvement on food prices (Table S4). Our estimates support the findings of Evenson and Rosegrant (14), who argue that in the absence of crop germplasm improvement in developing countries, higher food prices would have had serious negative implications on poverty and malnutrition.

The results of the GTAP model depend on a few key parameters regulating (*i*) the ease with which yields respond to increases in crop prices; (*ii*) the assumed productivity of the new forest and pasture lands that enter into crop production; (*iii*) the ease with which land is transformed from forests and pastures into crops; and (*iv*) the ease with which land switches among crops. These parameters are based on the available econometric

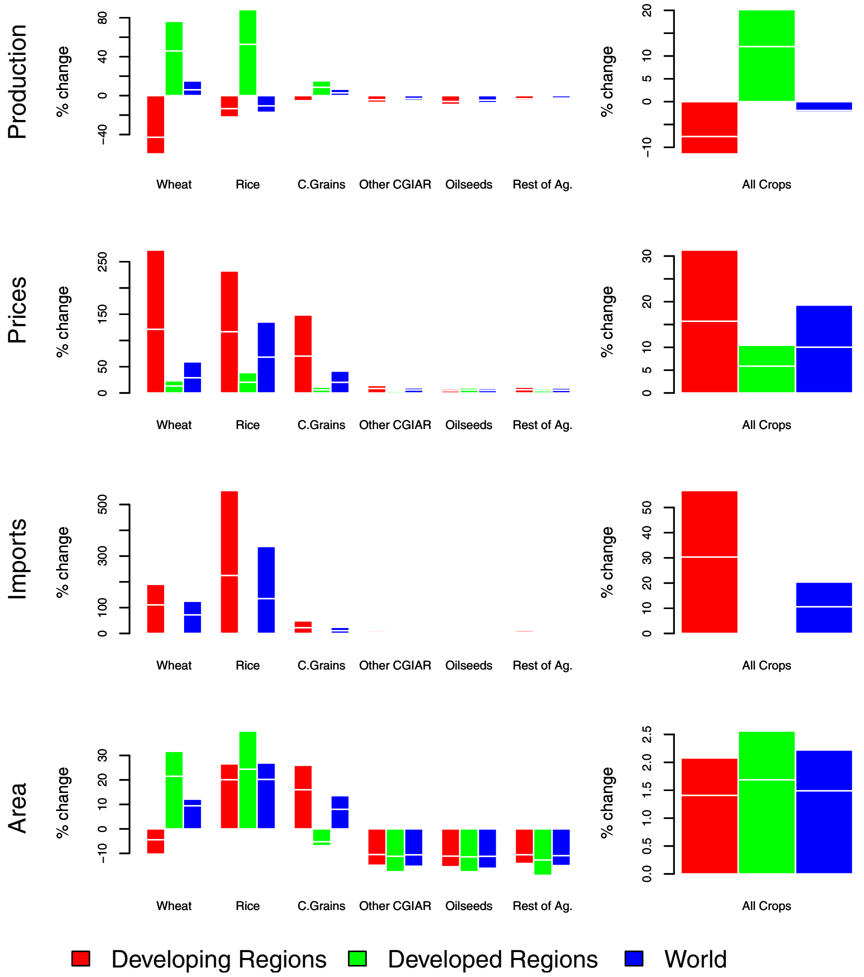

Fig. 2. Percentage changes relative to the baseline year (2004) in production, price, imports, and harvested area aggregated using as weights: output values (for prices), physical output (for production), and physical area. For each scenario the values for the lower and upper bounds are separated by a white line.

estimates and thus are inherently uncertain. To bound this uncertainty, we examine the sensitivity of our results to sensible parameter ranges following Hertel (19). More details can be found in *SI Materials and Methods*. The 95% confidence intervals (CIs) from our land cover/land use and emission results are shown as whiskers in the plots in Figs. 4 and 5. Only the results regarding forest conversion (Fig. 3) seem particularly unreliable, as evidenced by the wide CIs that include zero as a probable value. The CIs in Figs. 3–5 show that after taking into account parametric uncertainty, our results reinforce that the effects of CGI on changes in land use/land cover change and associated GHG emissions are positive but moderate, and are orders of magnitude lower than those estimated by Burney et al. (6).

In the counterfactual scenarios discussed here, crop germplasm improvement continued at its historical rate in developed countries—although in fact several studies have documented the significant positive spillover effects of CGIAR research on developed countries (21). A world not benefiting from crop germplasm improvement in key food security crops targeting developing countries, as modeled by our simulations, would consist of more people living in poverty and more people going hungry. It is valid to ask whether in the absence of crop germplasm improvement, the purely economic, rather drastic, counterfactuals presented in this article are ever likely to have occurred from a political perspective. *SI Materials and Methods* presents an additional simulation that holds baseline consumption of the crops indicated in Fig. 1 constant in the developing countries.

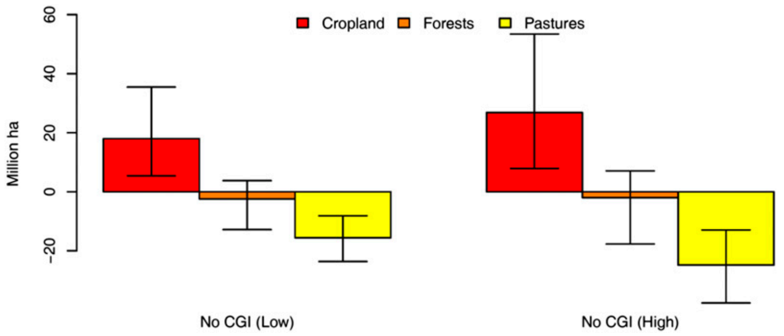

Fig. 3. Estimated land-use/land-cover change in 2004 under two scenarios: lower bound (*Left*) and upper bound (*Right*) effects of crop germplasm improvement. Whiskers reflect 95% CIs to uncertainty in the parameters regulating the ease with which yield responds to increases in crop prices, the assumed productivity of the new forests and pastures that enter into production, the ease with which land is transformed from forests and pastures into crops, and the ease with which land switches among crops.

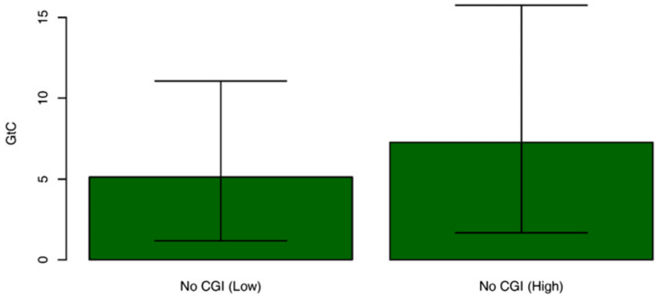

Fig. 4. Estimated increase in total GHG emissions (in Gt of CO_2) for the period 1965–2004 from land-cover change. Two scenarios and CIs as per Fig. 3.

To explore the effects on land-saving estimates of keeping developing country consumption levels constant, we ran alternative counterfactuals using the same productivity shocks but keeping consumption in the developing world constant in the baseline year (2004) (Table S6). These simulations give a range of 22–43 million ha (Table S7) land savings from crop germplasm improvement, suggesting that our main findings may represent lower bound estimates of the impact of crop germplasm improvement on land saving. However, this only serves to reinforce the point that even the estimates simulating a policy-mediated response are still well below projections using the global food equation, further underscoring the importance of considering market responses in assessing the effects of technological progress.

Discussion

GTAP-AEZ is one of a number of global economic models of land-use change (22), but most others, such as IMPACT (23), World Agricultural Trade Simulation Model (WATSIM) (24), Agriculture and Land Use Model (AgLU) (25), and the Forest and Agriculture Sector Optimization Model (FASOM) (26, 27), are partial equilibrium models that do not consider impacts through economy-wide effects or, most importantly for this study, through land market effects. Nonetheless, the introduction of land heterogeneity (AEZs), pasture and forest land-use, and land markets into CGE models is a relatively new enterprise. Although we have examined the sensitivity of our results to key parameters, the GTAP-AEZ model does not estimate the land conversion process (pastures or forests to cropland) directly for specific sites —only in the abstract at the level of the AEZ. Thus, to the extent that specific pastures or forests have heterogeneous emission factors access costs, the GTAP model could be over- or underestimating forest and pasture conversions and their associated emissions. Another limitation is that the model only considers conversions from pastures and forest to cropland, thus the role of transitions (forests to pastures to cropland) is overlooked.

It is important that claims of the land-saving effects of new technologies be carefully scrutinized, especially because many scientists continue to argue that they are saving forests through intensification on the forest margin (7, 28), and improved agricultural technologies are one of the most common mechanisms proposed for how to make reducing emissions from deforestation and forest degradation (REDD and REDD+) work (along with protected areas and community/local forest management). In particular, three critical factors influence whether new agricultural technologies reduce or increase pressure on forests: the location of productivity shifts (biased to forest margin or biased to established areas); the characteristics of the technological change (in particular, whether it is labor saving); and the demand elasticity for the agricultural product in question. Technologies that are predominantly adopted at or close to the forest margin and that produce a good with elastic demand on export markets will likely add to the pressure on the forest. Under these criteria, technological change in oil palm looks likely to induce further deforestation, in the absence of better regulation—oil palm production is located near forest margins, and there is potentially almost unlimited demand (29). Technologies for crops that have inelastic demand and that are predominantly adopted in existing cultivated areas will likely save land. Many of the CGIAR's mandate crops (e.g., rice, maize, wheat) fit this description. Finally, labor-intensive technologies adopted in traditionally cultivated areas may draw people away from the forest, further reducing pressure to clear forests (30).

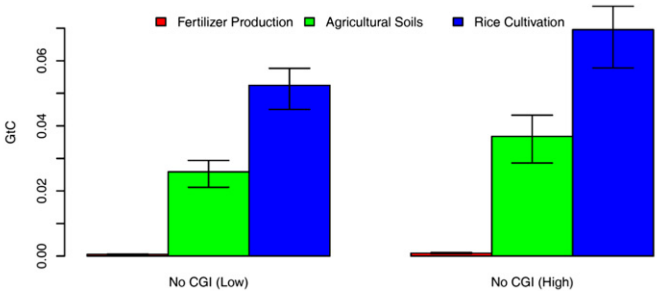

Fig. 5. Estimated agricultural emissions from changes in input use, agricultural soils, and rice cultivation associated with a counterfactual of no crop germplasm improvement over the period 1965–2004. Two scenarios and CIs as per Fig. 3.

We should also recognize that the impact of technological change on land-saving is likely to be a *weak* effect compared with the range of other exogenous factors driving land-use change and deforestation. Even for rapidly expanding commodities on the forest margin, such as pastures, soybeans, and oil palm, the effects of technological change on land expansion through returns to land are likely to be much smaller than effects of poor governance of land and forest resources. That is, expansion at the intensive margin through new technologies is unlikely to succeed if it is cheaper to expand at the extensive margin where forest land is readily available and poorly governed. Expansion at the extensive margin usually does not consider the real social value of forest resources foregone. Recent experience with better governance and monitoring of the Brazilian Amazon has shown a dramatic drop in rates of deforestation, even as commodity prices have risen sharply in the past 5 y (31–33). As this example demonstrates, for agricultural technologies to make a difference to slowing deforestation, their adoption by farmers has to be accompanied by a significant scaling up of enforcement of forest protection policies. This is consistent with one of the main findings of the long-run Alternatives to Slash and Burn program of the CGIAR: that raising agricultural productivity is a necessary but not sufficient condition for saving forests (34).

Land-cover change remains a dynamic process, with considerable potential for further deforestation to take place to meet the projected demands of a growing population, rising incomes, structural changes in diets, and particularly from new demands from biofuels. Conversion of natural grasslands and woodlands is likely to have lower costs in terms of ecosystem services foregone than conversion of tropical forests with high conservation values, carbon storage, and other services. Agro-ecological modeling of land suitability by the International Institute for Advanced Systems Analysis has identified 1,210 Mha of land that is still potentially suitable for conversion to rain-fed agriculture, even if the uncultivated land is likely more marginal than currently farmed land (perhaps with a replacement value of approximately 0.7). Well over half of this is forested, with two thirds in tropical areas. However, approximately 450 Mha is savannah or woodlands suited to crop agriculture, with two thirds of this located in sub-Saharan Africa and Latin America (35). Some continued expansion of agricultural land seems inevitable over the coming decades. The technological and governance challenge for humanity is how best to guide this expansion so that it takes place in areas where the environmental and social costs will be lowest.

As a framework for achieving this governance challenge, Rudel et al. (36) argue for more place-based agricultural policies in preventing deforestation. In general, the principle is that policies should strengthen agriculture near major centers of population to encourage intensification rather than extensification of agriculture at a distance, in response to rising demand from income and population growth. However, this vision will bump up against two major economic realities that will limit their political attractiveness to policy makers. First, policies that concentrate on "rewarding" landholders in favorable areas may be accused of being regressive and further marginalizing rural poor people. Second, with growing cities, the economic opportunity costs of farmland near cities increase as agricultural land is subject to competition from nonagricultural uses, making the implementation of these policies more expensive. To complement this place-based policy agenda, continued investment in agricultural productivity in the traditional areas for crop production, away from the forest frontier, should remain an important part of the global efforts in containing agricultural expansion. Nonetheless, we hope that this article serves to put expectations for "land-saving" benefits from these efforts in their proper context.

Materials and Methods

We use the GTAP-AEZ model, a modified version of the standard GTAP model that incorporates different types of land (Fig. S1). The GTAP-AEZ model is a multicommodity, multiregional computable general equilibrium, comparative static model that exhaustively tracks bilateral trade flows between all countries in the world and explicitly models the consumption and production for all commodities of each national economy (37). GTAP-AEZ has recently been validated with respect to its performance in predicting the price impacts of exogenous supply side shocks, such as those that might result from sudden technological change (38). The model used in this article incorporates different types of land. The foundations of these data are the global datasets for agricultural productivity (39) and forests (40). Lee et al. (41) used these data to develop a land-use and land-cover database that offers a consistent global characterization of land in crops, livestock, and forestry, taking into account biophysical growing conditions. We use the most recent version of this database, which defines 18 global AEZs and identifies crop and forest extent and production for each region by AEZ for specific crop and forest types in year 2004. The GTAP-AEZ framework used for this work introduces land competition directly into land supply (Fig. S2) via a two-tiered structure, such as that used by Keeney and Hertel (42). In the upper tier, crops compete with each other for land within a given AEZ. In the lower tier, crops as a whole compete with grazing and forestry for land within a given AEZ. In addition, different AEZs can be substituted in the production of any single agricultural or forest product. As explained in *SI Materials and Methods*, the shocks summarized in Fig. 1 are annualized over the period 1965–2004 and used to move the world economy from an initial equilibrium (characterized in the baseline year of 2004) to a counterfactual equilibrium absent of crop germplasm improvement in developing countries.

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