Agricultural intensification and changes in cultivated areas, 1970–2005

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Does the intensification of agriculture reduce cultivated areas and, in so doing, spare some lands by concentrating production on other lands? Such sparing is important for many reasons, among them the enhanced abilities of released lands to sequester carbon and provide other environmental services. Difficulties measuring the extent of spared land make it impossible to investigate fully the hypothesized causal chain from agricultural intensification to declines in cultivated areas and then to increases in spared land. We analyze the historical circumstances in which rising yields have been accompanied by declines in cultivated areas, thereby leading to land-sparing. We use national-level United Nations Food and Agricultural Organization data on trends in cropland from 1970–2005, with particular emphasis on the 1990–2005 period, for 10 major crop types. Cropland has increased more slowly than population during this period, but paired increases in yields and declines in cropland occurred infrequently, both globally and nationally. Agricultural intensification was not generally accompanied by decline or stasis in cropland area at a national scale during this time period, except in countries with grain imports and conservation set-aside programs. Future projections of cropland abandonment and ensuing environmental services cannot be assumed without explicit policy intervention.

land sparing | land use

Does the intensification of agriculture on some lands spare other lands from cultivation? The significance of the answer to this question looms large as the human footprint on Earth grows and society searches for a more sustainable relationship with nature. Our ability to supply the growing global demand for food, fiber, and fuel, while maintaining a landscape able to provide a full suite of environmental services (1), hinges on our ability to produce more on less land.* The intensification of agriculture alone does not ensure that an environmentally sustainable landscape matrix will be maintained, but it is an essential step in the process because crop and pasture lands comprise about one-third of Earth's ice-free surface (2).

Influential agricultural scientists have linked agricultural intensification to land-sparing in various ways. Borlaug (3) posits that per hectare increases in agricultural productivity lead to a reduced demand for croplands, potentially sparing these lands for other uses. Observing that cultivated land areas have increased more slowly than might be expected given increases in population and changes in consumption patterns, Waggoner and Ausubel (4) project that intensified production could reduce the global extent of croplands by 230 million ha (an area more than three times the size of France) by 2050.

Theoretically, agricultural intensification sets in motion two countervailing forces, one that increases and another that reduces cultivated areas. Initially, intensified production provides farmers with higher yields per hectare and growth in their gross income. This prospect may induce them to expand the area that they have under cultivation. If demand for the products is relatively inelastic, the increase in supply that results from the aggregation of individual farming decisions will result in a decline in crop prices. Arguments for the land-saving effects of intensification emphasize this second stage of the process in which price declines dissuade farmers from expanding the area that they devote to cultivating these crops (5). The increased yields that set these processes in motion may stem from changes in technology, but they may also stem from the knowledge that farmers accumulate about a place. As farmers, over time, come to know the soils in a place better, they confine agricultural production to the most fertile lands that respond better to additional inputs (6). Cropland may change little in extent or it may decline as farmers abandon their less-productive fields. The lands abandoned by farmers have the potential to become places that provide enhanced environmental services (3, 4, 7–10). In sum, as agricultural yields increase, prices drop and cultivated areas decline (Fig. 1). At a societal level, a forest transition may ensue, with forests spreading across the abandoned lands and overall forest cover increasing after a long period of decline (6, 11).

It is possible, however, particularly if demand for the output good is relatively elastic, that the increase in supply does not result in a large price decline and the overall incentive for higher production by using more land remains in place (12–14). In these instances, agricultural intensification does not deter expansion in croplands, and threats to environmental services, especially at the landscape or regional levels, may grow. Empirical studies, focused overwhelmingly on local and regional scale changes, provide evidence for both land-consuming and land-sparing effects from intensification (15–18). Analysts working at the global scale have modeled the land-sparing effect rather than examining historical instances of it (4, 7, 9). They have used recent agricultural, demographic, and economic data to construct equations that predict changes in cultivated areas. These models then provide estimates of the magnitude of the land-sparing effect occurring, prospectively, between 2005 and 2050 (9) or, retrospectively, between 1960 and 1991 (7).

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*Increased production alone does not ensure that demand will be fulfilled adequately. More equality in entitlements to production is necessary as well (33).

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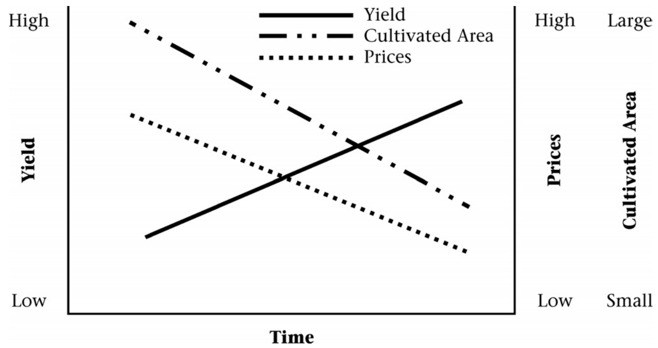

Fig. 1. Borlaug hypothesis: Hypothesized relationship between changes in yields per hectare, prices, and cultivated areas.

Researchers have not yet examined actual historical episodes in which agricultural intensification has led to cropland abandonment or restrained agricultural expansion on a large scale. This type of investigation faces two methodological challenges. The first one involves the measurement of spared land. Data on the global extent of abandoned cropland do not exist. Satellite images can detect the presence or absence of old-growth forest, but they have difficulty distinguishing idled land from active cropland at a global scale.

Agricultural statistics, collected from nations by the Food and Agricultural Organization of the United Nations (FAO), provide a way to investigate at a global scale the first link in the intensification–land-sparing causal chain, between agricultural intensification and cultivated areas. To do so, we must address a second methodological challenge stemming from the possibility that farmers will devote freed-up fields to other crops when they reduce cultivated areas of intensified crops. If large numbers of farmers make these shifts, declines in cultivated areas of intensified crops will not provide the possibility for environmental gains. The way that we have constructed the dependent variable for our multivariate analyses, outlined in *Methods*, and three supplementary analyses described in section A of the *SI Appendix* suggest that this circumstance has not occurred often enough to invalidate analyses of the global scale links between yield increases and changes in cultivated areas.

We address the yield increase cultivated area hypothesis with data from the United Nations on the agricultural production of countries (19). Officials at the FAO have outlined rules for collecting data and defining measures, but countries may use different methods in compiling the data that they report to the FAO. Despite the inevitable errors associated with this procedure, the FAO archive contains the only historical and worldwide data on agricultural production, so it is indispensable for addressing this empirical question. Given the importance of the intensification–land-sparing hypothesis, working with imperfect data seems warranted. Analyses with and without countries with the lowest-quality data reinforce this conclusion because the substantive findings remain the same.

We examine the historical record of agricultural intensification and change in cultivated areas, first at the global scale for ten crops from 1970–2005, and then, in a more historically detailed way, at a national scale for the same ten crops from 1990–2005. The ten crops, representing 57% of Earth's cropland, are corn (maize), wheat, rice, soybeans, potatoes, bananas, cocoa, coffee, sugarcane, and cotton. Our analyses address whether, when, and where intensified cultivation of these crops (measured by increasing yields of crops per hectare) reduced cultivated areas or restrained their expansion.

The analysis examines the intensification–cultivated area relationship in a context shaped by other variables that may have induced declines in cultivated areas. Increased imports of grains may have released less-productive local lands from agricultural production and promoted land sparing. Conservation set aside programs, enacted primarily in China, Europe, and North America and designed in most instances to encourage the abandonment of erosion-prone agricultural lands (20), may also have induced declines in cultivated areas. Looking at instances in which yield increases coincided with either static or declining cropland areas makes it possible to assess these hypotheses.

The analysis begins with a description of global trends in yields, prices, and cultivated areas between 1970 and 2005. Then it examines the yield–cultivated area dynamic in a more detailed way, with bivariate and multivariate analyses, over a shorter time period—between 1990 and 2005—in regions, countries, and agricultural sectors. Both periods, 1970–2005 and 1990–2005, represent suitable periods to test the proposed hypothesis because they saw continued yield increases across a wide range of crops and declines in the prices of agricultural commodities. The 1970s saw sharp declines in the prices of agricultural commodities. Between 1990 and 2005 the prices of major grains declined between 15.7% and 34.1% in real (purchasing power parity) terms (see Table 1 and Fig. 2) (21). Under these circumstances, we might expect to see declines or at least stability in cultivated areas after intensification because, under price pressure, farmers might decide not to cultivate less-productive fields.

Results

Global increase in cultivated area was less rapid than gains in population and income between 1970 and 2005. During the 35-year period, the world population grew by 74.3%, the world per capita income grew by 87.2%, and total food production increased by 123%. The cultivated area for the ten major crops increased by only 25.7%. The worldwide increase in cultivated area for all crops was even more modest, 21.3% (19, 22). Despite the slow rate of increase in cultivated land, there are few

Table 1. Has agricultural intensification reduced cultivated areas? Trends for ten crops by region, 1990–2005

Regions	Production 1990, yield/land area	Production 2005, yield/land area	% Change, 1990–2005, yield/land area	Observable regional land sparing?
SubSaharan Africa	1,449/44,725	1,642/51,138	+13.3/+14.3	No
Near East & North Africa	4,175/29,265	5,479/31,319	+31.3/+7.0	No
Europe	5,045/53,815	5,968/54,565	+18.3/+1.4	No
East and South Asia	2,038/277,626	2,992/300,100	+46.8/+8.1	No
Central Asia	2,223/49,044	3,148/49,363	+41.6/+0.6	No
Oceania	4,795/10,214	5,000/13,735	+4.3/+34.5	No
Anglo-America	6,529/100,427	8,036/99,532	+23.1/−0.8	Yes
Middle America & Caribbean	2,194/16,547	2,692/14,854	+22.7/−10.2	Yes
South America	1,994/64,933	2,678/85,719	+34.3/+32.0	No
World	3,096/646,596	3,838/700,325	+ 24.0/+8.3	No

Yields in kg/ha. Land area in thousands of hectares. (Source: FAOSTAT, 2008.)

SEE COMMENTARY

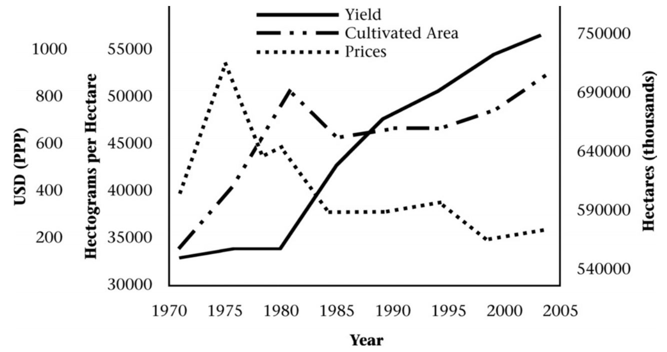

Fig. 2. Global trends over time in yield, cultivated area, and prices for ten major crops.

historically observable instances in which yield increases appear to have brought about declines in cultivated land. Fig. 2 illustrates this empirical point. It outlines the observed relationships between agricultural yields (in hectograms per hectare), prices, and cultivated areas between 1970 and 2005 for the ten crops. Only between 1980 and 1985, in the aftermath of a sustained decline in agricultural commodity prices and a steep rise in yields during the 1970s, does agricultural intensification appear to induce declines in cultivated areas.

Between 1990 and 2005 a similar pattern occurred, with robust increases in global population (23%) and global per capita income (36%) coupled with slower growth in cultivated areas (8.3%). There is, however, no association ($r = 0.017, p = 0.606$) between changes in yield and changes in cultivated areas across 961 agricultural sectors in 161 countries during the 15-year period. Increases in yield and declines in crop area do occur in some countries. Thirty-four of the one hundred sixty-one countries exhibited both yield increases and declines in cultivated areas between 1990 and 2005. These countries cluster geographically to some extent, with a large number of them occurring in southeastern Europe (Austria, Greece, Hungary, Italy, Croatia, Serbia, Switzerland, and Turkey). Intensification-associated declines in cultivated areas correlate modestly ($r = 0.187, P = 0.032$) with forest cover gains (as tabulated by the FAO) for the same period. Countries with rising yields and declining cropland areas increased their per capita imports of grains from 84.7–106 kg (25.1% increase) compared with an increase from 96.7–101. 2 kg (4.7% increase) for other nations ($P > 0.001$) during the 1990–2004 period.

The pattern of rising yields and declining cultivated areas occurred in other circumstances as well. Middle America exhibits this pattern between 1990 and 2005 (Table 2). (Section B of the *SI Appendix* contains a list of countries in each region.) This region experienced a net decline in cultivated area of just under 1.7 million ha during the 15-year period. The decline in cultivated land was concentrated in just four of the 130 agricultural sectors across 19 countries in the region. Sugar in Cuba (−903,000 ha) and corn (−732,000 ha), soy (−198,000 ha), and wheat in Mexico (−298,000 ha) saw losses in cultivated area totaling more than 2.1 million ha over fifteen years. Analyses of changes across crops rather than across regions provide another way to assess the link between yield increases and declines in cultivated areas. Of the ten crops considered between 1990 and 2005, only coffee and wheat exhibited a pattern consistent with intensification-induced declines in cultivated areas (Table 1).

Multivariate analyses examine the coincidence of agricultural intensification with declines or stasis in cultivated areas across 145 nations below and, separately, across 927 agricultural sectors within those nations (section C of the *SI Appendix*).

In Eq. **1**, we measure the effect through changes in the ratio of yields to total area cultivated. When yield goes up and the area cultivated goes down, this ratio increases. This ratio also increases when yield goes up and cultivated area does not change. At the national scale, reported in Eq. **1**, countries with conservation set-aside programs have rising yields and declining or static cultivated areas. These countries also tend to import increasing amounts of cereals per capita. The imports reduced the pressure for production from local lands and, in so doing, reduced cultivated area. The same patterns recur in a weaker way in analyses of the yield/area relationship across agricultural sectors in section C of the *SI Appendix*. The pattern of rising yields and declining or static cultivated areas occurs more frequently in countries with set-aside programs and rising cereal imports. Conservation set-aside programs induce this pattern with wheat and rice but not with other crops.

Discussion

For the past twenty years, many analysts have argued that agricultural intensification, by raising yields per hectare and thereby increasing the supply of foodstuffs, would depress the prices of agricultural commodities and induce farmers to retire lands or refrain from cultivating lands that they would have otherwise cultivated (5). Cultivated areas increased more slowly than world population between 1970 and 2005, but actual declines in cultivated area occurred infrequently at global, regional, and national scales. The most common pattern involved simultaneous increases in agricultural yields and cultivated areas. This pattern recalls the Jevons Paradox, after William

Table 2. Has agricultural intensification reduced cultivated areas? Global trends by crop, 1990–2005

Crop	Trends, real prices, 1991–2004	Production: 1990, yield/land area	Production: 2005, yield/land area	% Change, 1990–2005, yield/land area	Observable land sparing?
Grains					
Corn	−32.7%	3,680/131,324,621	4,899/145,498,907	+33.1/+10.8	No
Rice	−24.7%	3,528/146,974,144	4,088/154,475,470	+15.9/+5.1	No
Soybeans	−34.1%	1,96/57,193,392	2,301/93,393,438	+21.4/+63.3	No
Wheat	−15.7%	2,561/231,278,715	2,839/221,438,219	+10.9/−4.3	Yes
Tropical Crops					
Bananas	−30.0%	13,898/3,324,555	16,754/4,144,895	+20.5/+24.6	No
Cocoa	−2.4%	444/5,709,802	540/7,431,303	+17.9/+30.1	No
Coffee	−42.8%	534/11,355,978	701/10,420,008	+31.2 −8.2	Yes
Sugarc..	−27.8%	61,667/17,079,889	65,205/19,868,678	+5.7/+16.3	No
Miscellaneous					
Potatoes	−22.0%	15,131/17,624,200	16,967/18,968,309	+12.1/+7.6	No
Cotton	−41.8%	560/33,100,017	712/34,840,407	+27.3/+5.3	No

Yields are in kg/ha. Land area is in thousands of hectares. (Sources: FAOSTAT, OECD-FAO World Food Outlooks. Accessed March–October, 2008.)

$$
\begin{aligned}
&\underset{\text{(yield/area cultivated)}}{Y\ (\Delta,\ 90\text{-}05,\ \text{in}} = -.03 + \underset{(.06)}{.36}\ \text{Conservation***}\ \text{Set-Aside Prog.} - \underset{(.08)}{.15\%}\ \text{1990 Pop* in Ag.} + \underset{(9)}{31}\ \text{1990 Land Area (\%)** in Crops} \\
&\quad - \underset{(.04)}{.16}\ \text{Ag. Prod.,*** in 1990} + \underset{(.35)}{1.23}\ \text{Cereal Imports*** per capita, 1990}
\end{aligned}
$$

Eq. 1. Agricultural intensification and cultivated area dynamics, 1990–2005: determinants by nation. The numbers are unstandardized coefficients and below them are their stand errors. ***, $p < .001$; **, $p < .01$; *, $p < .10$; adjusted $r^2 = .265$; $n = 145$.

Stanley Jevons, who observed that in 19th-century England growing efficiency in the use of coal increased rather than decreased its use (23). With the exception of the early 1980s, demand for agricultural commodities during an era of globalizing markets remained sufficiently elastic to induce farmers, on net, to cultivate more land even as they produced more crops per hectare.

Historical circumstances help to clarify the relationship between intensification and changes in cultivated areas. Shifts in international political economy played an important role in the declines of cultivated area in Middle America and the Caribbean between 1990 and 2005 (Table 2). With the collapse of the Soviet Union, Cuba lost a protected market for the sale of most of its sugar crop. In response, the Cuban state cut back on the cultivation of sugarcane. Cultivated areas for all crops declined by 23% in Cuba between 1990 and 2005. With the advent of the North American Free Trade Agreement (NAFTA), Mexico was flooded with inexpensive, subsidized American crops (24), and Mexican farmers reduced the land that they planted in corn, soy, and wheat. Cultivated areas of tropical crops in Mexico, like coffee and bananas, did not decline between 1990 and 2005, presumably because NAFTA did not reduce the prices for these commodities.

Political events also figured centrally in the worldwide declines in coffee and wheat hectarage (Table 1). With the collapse of the coffee cartel in the early 1990s, producers lost protected markets in affluent nations, and, in a pattern that recalls the Cuban–Soviet experience with sugar, coffee growers in large, producing nations like Brazil, Colombia, and Cote D'Ivoire cut back on the area under cultivation. These cutbacks more than counterbalanced increases in coffee lands in Vietnam and Indonesia. Wheat presents a somewhat different picture. Declines in cultivated areas occurred in just a few countries, Canada, China, and the United States. Between 1990 and 2005, wheat hectarage in these three countries declined by 19.7 million ha whereas it increased by 9.9 million ha elsewhere in the world. New public programs that paid farmers in cash or kind for retired lands began in China and the United States, the two countries with the largest areal declines in wheat cultivation. In China the "Grain for Green" program took large, upland areas out of cultivation (25). In the United States, wheat farmers in the Great Plains enrolled large areas prone to crop failure in the Conservation Reserve Program (26).

In some instances, policymakers intended to reduce cultivated areas (e.g., China) whereas in other instances new policies produced unintended reductions in cultivated areas (e.g., Mexico). These declines in cultivated areas, especially in the case of NAFTA, imposed significant social costs on small farmers, as cheap agricultural imports and the loss of price supports drove many of them out of agriculture. The policy changes often occurred in concert with increases in cereal imports. Countries that enacted conservation set-aside policies increased their cereal imports per capita by 42.4% between 1990 and 2004 compared with a 3.5% increase in countries that did not enact set aside policies during this period ($P < 0.001$).

The hypothesized first link in the intensification–land-sparing hypothesis, between rising yields and declining cultivated areas, does not generally characterize agricultural sectors between 1990 and 2005. It does characterize the agricultural sectors in 34 of the 161 nations. The circumstances surrounding the yield increase–cultivated area decline in those 34 countries should indicate something about the mix of conditions that promotes the intensification–declining cultivated area pattern. In these places, grains imported from abroad substituted for crops grown at home, and this substitution, coupled with conservation set-aside programs, encouraged declines in cultivated areas at home (Eq. **1**). Even when agricultural commodities declined as much as 15% to 35% in price over a decade, intensification-associated declines in cultivated areas only occurred when market integration drove smallholder farmers and inefficient forms of cultivation out of agriculture (e.g., Mexico) or when merchants increased their imports of foodstuffs and governments provided incentives for farmers to conserve land.

The global scale analyses, the cross-national analyses, the case studies, and the cross-sectoral analyses explain some declines in cultivated areas and miss others. For reasons outlined in the *Methods* section, this analysis does not include the livestock sector. Approximately one-third of all global cropland now produce feed grain for animals, and significant but difficult-to-measure intensification–cultivated area dynamics may occur in this sector (27). In addition, given the historical limits of this analysis, the findings reported here do not reflect the most recent impacts of increased biofuels production on cultivated areas. Also, swidden cultivation, involving mobile cultivators in remote rural locations, remains poorly estimated in FAO data[†]. The apparent decline in the numbers of shifting cultivators in Southeast Asia during the past three decades has probably reduced the magnitude of this measurement error (28).

Other potential sources of uncertainty do not seem disabling. The agricultural sector analysis (section C of the *SI Appendix*) at a lower level of aggregation than the country level analysis (Eq. **1**) shows the same pattern of substantive findings. The subset analysis of the country-level sample, as explained in the *Methods* section, eliminates countries with the worst data and finds the same patterns. Finally, the construction of the dependent variable and the supplementary analyses reported in section A of the *SI Appendix* suggest that the declines in the cultivated areas of our ten crops do not usually imply increases in the cultivated areas of other, unaccounted-for crops.

Amid these uncertainties, the analyses reported here permit some initial conclusions about the agricultural intensification–cultivated area relationship. In most countries yields increased, but cultivated areas did not decline. This pattern raises questions about the ability of agricultural intensification to spare land, at least through declines in cultivated areas. In 21% of the countries, mostly in temperate locales, a political–economic dynamic involving the creation of policies to spare land, coupled with larger imports of grain, contributed to a pattern of rising yields and falling cultivated

[†]The FAOSTAT website, http://faostat.fao.org/site/377/default.aspx#ancor, indicates that they include shifting cultivation in their data about "primary crops". Because FAO defines idle land farmed during the past five years as cultivated, the long-fallowed lands (>5 years) of many shifting cultivators would not count as "cultivated". The subset analyses suggest the errors here are not so large as to threaten the validity of our analysis. First, because the countries with the lowest-quality FAO data tend to be poor, tropical countries with large numbers of shifting cultivators, datasets without these countries should contain fewer errors attributable to omitted shifting cultivators. Because the substantive findings do not change when we omit poor tropical countries with low-quality data from the analyses, it would seem that noisy data on shifting cultivators has not affected the analyses reported here.

Table 3. Variable definitions and sources

Term and applicable year	Definition	Source
Acreage, 1990	Thousands of hectares cultivated for a particular crop.	FAOSTAT. Accessed at: http://faostat.fao.org/site/567/default.aspx.
Cereal imports per capita, 1990.	Tons of cereals imported in 1990/population of the nation.	Earthtrends. Accessed at: http://earthtrends.wri.org/.
Conservation set-aside programs, 1990	A binary variable; 1, program; 0, no program.	A list of the countries with programs and the sources for this information are provided in section D of the *SI Appendix* in supporting information.
Gross domestic product per capita, 1990	In U.S. dollars.	Penn World Tables. Accessed at: http://pwt.econ.upenn.edu/.
Land sparing, 1990–2005	ln (2005 Yield/2005 Area Cultivated) − ln (1990 Yield/1990 Area Cultivated).	
Irrigated land, 1990	Proportion of national land area that was irrigated in 1990. Irrigated acreage in hectares/national land area in hectares.	Earthtrends. Accessed at http://earthtrends.wri.org/
Production, 1990	In tons.	FAOSTAT. Accessed at: http://faostat.fao.org/site/567/default.aspx
Proportion of the national population that was economically active in agriculture, 1990	Given as percentage.	FAOSTAT. Accessed at: http://faostat.fao.org/site/567/default.aspx.
Proportion of national land area under cultivation for this crop, 1990	Hectares cultivated in 1990/national land area.	FAOSTAT. Accessed at: http://faostat.fao.org/site/567/default.aspx.
Regional dummy variables	1, in region; 0, outside of region.	For the geographical boundaries of the regions, see section A of the *SI Appendix*.
Yield, 1990	In kg/ha.	FAOSTAT. Accessed at: http://faostat.fao.org/site/567/default.aspx.

areas. By implication, increasing yields cannot be assumed to increase cropland abandonment without policies that encourage abandonment. This link between yield increases and cultivated area declines emerged during a historical period marked by agricultural surpluses and declining prices for agricultural commodities. Changes in these underlying conditions could sever the links outlined above. For example, when prices of agricultural commodities rose dramatically between 2005 and 2008, the European Union reacted by eliminating the conservation set aside provisions in their Common Agricultural Policy (29). In other words, the continuation of some conservation programs appears to have depended, in recent decades, on continued agricultural intensification with accompanying surpluses of agricultural commodities.

The links between declines in cultivated areas, conservation policies, international trade, and agricultural intensification may have recently changed in one more important way as the prospect of payments for environmental services (PES) in the tropics has become a salient part of a proposed, worldwide climate-stabilization policy. Both reducing emissions from deforestation and degradation and PES on abandoned agricultural lands only become politically palatable policy options when crop yields rise on the remaining lands and temper commodity price increases. The increased demand for biofuels, coupled with growth in the feed grain trade (27), has contributed in recent years to high agricultural commodity prices, so the political conditions that encourage the emergence of an intensification/static, or declining cultivated area dynamic seem precarious (30). In this context, the importance of coupling agricultural intensification with land sparing should grow and make understanding the agricultural intensification–land-sparing relationship an important priority for sustainability science.

Methods

Data. The analyses presented here examine trends in agricultural productivity and cultivated areas for 15-year (1990–2005) and 35-year (1970–2005) periods across 161 nations for ten important crops (totaling 961 agricultural sectors): three grains (corn, rice, and wheat), four tropical crops (bananas, cocoa, coffee, and sugarcane), and three other crops (soybeans, potatoes, and cotton). The data on trends in yields and area planted come from a statistical database, FAOSTAT, created by the Food and Agricultural Organization of the United Nations. The ten crops represent a purposive sample, chosen because they figure centrally in larger global problems. Trends in yields and areas cultivated for the three cereals and soybeans affect global efforts to feed poor people. Trends for the four tropical crops influence rates of tropical deforestation. The consumption of potatoes has increased substantially in developing countries. Finally, cotton represents an important nonfood commodity affected in recent years by the spread of genetically modified varieties. The large numbers of crops, ranging from 15–120 crops, for each country, and the small extent of the cultivated areas for most crops made it practically impossible to conduct a study that includes all crops. Of the crops excluded from the analysis, only secondary grain crops (barley, sorghum, millet, and oats) covered large areas (≈15%) of global cropland. We considered adding pasture to the analysis because livestock and their pastures have enormous environmental impacts. Measurement problems made it difficult to do so. Although increased stocking rates for cattle on pastures (pasture/cattle) would provide a measure of intensification, confined cattle and feed grains imported from outside of the country in question (27) would skew this measure in an erroneous way.

Fig. 2 presents changes in cultivated area, real price, and yield for all ten crops for the 1970–2005 period. The average for yield across the ten crops has been weighted by the land area for each crop, so, for example, changes in the yield for wheat (planted over large areas) affected trends in yields more than did changes in the yield for cocoa (planted in smaller areas).

Real prices for specific crops from 1970–2000 are available from FAO (31). Of the ten crops, only bananas and potatoes deviated significantly from the historical trend reported in Fig. 2.

Tables 1 and 2 present aggregated descriptive statistics for trends in yields and cropland by crop (Table 1) and by region (Table 2). The observed trends in yield and cropland in these tables could be affected by extraneous influences. For example, if the composition of what is grown in the countries of a region shifts dramatically, with some crops disappearing and other crops appearing, differences in productivity per hectare between the crops would change the region-wide averages in Table 2. Similarly, a decline in the cultivated area of a crop in Table 1 does not produce environmental benefits if a farmer just converts a field from that crop to another crop. We discuss this possibility more completely in *Measures* and in section A of the *SI Appendix*.

Measures. Table 3 lists the definitions and sources for the variables used in the multivariate analyses presented in Eq. **1** and section C of the *SI Appendix*. Section D of the *SI Appendix* lists the countries with conservation set-aside programs and the sources for this information. Measures for the variables in the multivariate analyses take conventional forms with one exception, the yield/cultivated area ratio. We wanted to capture the dynamic of rising yields and declining cultivated areas in a single measure to simplify the quantitative analysis. The change in the ratio of yield (in thousands of hg) to total area cultivated (in millions of ha) expresses this relationship in a straightforward way. To the extent to which agricultural intensification reduces the cultivated area of a crop, this ratio should increase from time 1 to time 2. It would also increase when cultivated area does not decline, but stays roughly the same while the volume of production goes up. This measure takes the following form:

$$Y = \ln\,(2005\ \text{yield}/2005\ \text{area cultivted}) \\ -\ln\,(1990\ \text{yield}/1990\ \text{area cultivated}).$$

Positive numbers would indicate the presence of a dynamic of an ever-more productive agriculture practiced on a diminishing number of fields. Negative numbers would suggest no such effect. Alternative formulations of the dependent variable produce substantively similar results. Both grain imports and conservation set-aside variables are, for example, significant predictors of declines in cropland between 1990 and 2005.

This measure of the yield/cultivated area dynamic registers changes that occur when farmers convert their fields from one to another of the ten crops in the analysis. For example, when an American farmer converts a soybean field into a corn field, productivity gains over time from that shift would be captured by this measure because it pools the yield increases and cultivated area changes for both corn and soybeans. It is true that our measure could not capture the productivity effects of a conversion of a corn field into a barley field because barley is not one of the ten crops under analysis. Analyses in section A of the *SI Appendix* suggest that the magnitude of errors introduced this way is small for three reasons. First, differences in the agroecological requirements for crops reduce the number of possible shifts from crop to crop. Second, large-scale, asymmetrical shifts in which one crop grows in extent at the expense of another crop—the kind of shift necessary to introduce a large error term into the analysis—occur rarely. Of 56 bivariate analyses of crop-to-crop shifts, including pasture-to-crop shifts, only one pair of crops, sugarcane and pasture, exhibited this type of inverse association (Table A1 of the *SI Appendix*). Third, declines in cultivated area of one crop could, however, be recouped by gains in the cultivated areas of many other crops. If so, trends in the cultivated area of the losing crop would be unrelated to the total amount of agricultural land in a nation. In fact (Table A2 of the *SI Appendix*), losses in cultivated area in one crop occur most frequently in nations where agricultural land overall is in decline. Changes in seven of eleven agricultural land uses (including pasture) associated positively with changes for all agricultural land. Section A of the *SI Appendix* describes these analyses more fully. In sum, the pooled aspect of the yield–cultivated area variable, coupled with the three analyses in section A of the *SI Appendix*, strongly suggest that conversions of fields from one crop in the analysis to another crop outside the analysis between 1990 and 2005 do not constitute an important source of error.

Multivariate Analyses. We carried out weighted OLS analyses of the data, regressing the yield/cultivated area ratio on a set of independent variables that includes grain imports and conservation set aside programs (yes/no). To accord equal importance to equal-sized land areas, we weighted the analyses by the extent of the cultivated area in 1990 (in the ten crops in the national analysis, in individual crops in the agricultural sector analysis). The equations in Eq. **1** and section C of the *SI Appendix* do not exhibit problems of multicollinearity. The variance inflation factors usually range between 1.0 and 2.0, with the highest being 3.4.

We ran an additional set of multivariate analyses to assess the robustness of our substantive conclusions. The quality of FAO's forest cover data recently received a searching critique (32), so the possibility exists that FAO's agricultural land use data contains so much error that it should not be used in a global scale analysis of agricultural intensification and land sparing. Sensitive to this possibility, FAO rates the quality of the data that it receives from each country, assigning scores of ''good'', ''fair'', and ''poor'' to countries. Countries with poor ratings typically do not provide FAO with sufficient information about how they collected the data. Thirty-one countries, mostly smaller and poorer nations, currently have poor ratings for data quality. We assessed the robustness of our substantive conclusions through a subset analysis in which we reran the analyses reported in Eq. **1,** Tables 1 and 2, and section C of the *SI Appendix* on the subsample of countries that received good or fair data quality ratings. The substantive patterns in Eq. **1** and Tables 1 and 2 remained the same in the analyses of countries with better data. In the crop-specific analyses reported in section C of the *SI Appendix*, the partial regression coefficients remained substantively unchanged in ten of the eleven equations. In the equation for rice, the conservation set-aside coefficient became insignificant. The overall similarity in substantive findings with and without the poorly rated data suggests that the conclusions from our analyses of agricultural intensification and changes in cultivated areas are robust.

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SI Appendix A: Do declines in cultivated areas for one crop precipitate increases in cultivated areas for other crops?

The significance of our findings hinges on the degree to which declines in cultivated areas in one crop lead either to land saving or to an increase in land used for another crop. As farmers, for example, decrease the number of fields in which they cultivate soy, do they increase the amount of land that they devote to barley? If so, then gains in productivity may reduce acreage in a particular crop, but acreage in other crops will climb. Under these circumstances he intensification – cultivated area decline dynamic would produce little land saving and investigations of the causes for intensification – cultivated area changes based on some but not all crops, like this study, would not be indicative of patterns in total crop area. For this reason, it is important to try and ascertain, to the extent possible given data limitations, the degree to which farmers shift between crops in large scale, asymmetrical ways. If they do make these shifts frequently from crops in our analysis to crops outside our analysis, it would undermine the validity of our work.

Three types of evidence allow us to estimate the extent of large scale, asymmetrical crop shifting. First, using FAO agro-ecological zone data for crops (1), we can calculate the degree of overlap between zones that are suitable for the ten crops in our analysis. A correlation matrix from these analyses reveals three agro-ecological clusters among the ten crops: wheat – potatoes, corn-soy-cotton, and sugarcane-coffee-bananas-cocoa. For example, we might expect to see farmers shift from growing cotton to growing soy because the extent of overlap in suitable zones is very high (.97), but we would not expect to see a farmer shift from wheat to rice because the extent of the overlap in suitable zones is quite low (.15). Seventy-four percent of the pairs of crops in our analysis (coffee and cocoa excluded because of lack of data) showed less than 70% overlap. Because this analysis includes even minimally suitable sites for crops, it probably overestimates the possibilities for crop shifting. Farmers use much more fine grained criteria in their decision making about crops for particular fields than we have used here. In sum this analysis demonstrates that farmers' possibilities for crop shifting are substantially limited by agro-ecological conditions.

Second, the large scale, asymmetrical shifts from one crop to another crop could, depending on the crops involved, introduce error into our analyses. These crop to crop shifts in response to changing yields should, if they occur, leave markers in the aggregate data on crops. In particular we would expect to see inverse correlations between the two crops. To be sure, farmers will shift back and forth between crops, but it is only large scale, asymmetrical shifts from one crop to another that would threaten the validity of our analyses. To ascertain the frequency of these inverse associations, we cross-correlated changes in cultivated areas for all ten crops plus pasture for the 1990 to 2005 period (Table A1). Of the 55 correlations in the table, only one, between pasture and sugarcane, exhibits the inverse association we would expect to see if declines in the cultivated areas of one crop are precipitating increases in the cultivated area of another crop.

Of course the declines in the cultivated areas of one crop could produce a less conspicuous pattern of expansion in other crops in which the increases in cultivated areas spread across several other crops. If this pattern prevails, we would expect that the decline in the cultivated area for one crop would not extend to the cultivated areas of other crops in the country. There should, in fact, be a disjunction between the trends in the one crop and the national trends in cultivated areas if asymmetrical crop shifting occurs frequently between that crop and other crops. Table A2 correlates the changes in cultivated areas for eleven crops (the ten crops plus pasture) with changes in the total agricultural land (pastures plus cropland) in nations. Seven of the eleven crops show significant (.10 > p.) positive associations between trends in the cultivated areas for the specific crop under study and trends in cultivated areas for all crops in a nation. We would not expect to see these positive associations between trends for individual crops and the aggregated cultivated areas for nations if the declines in cultivated areas of one crop were accompanied by increases in the cultivated areas of other crops. The prevalent pattern is that the changes in the cultivated areas for one crop seem to get repeated for other crops in a nation. Given that the cultivators are subject to a common set of political economic conditions, this finding should not seem surprising.

The preponderance of the evidence from these three analyses suggest that farmer decisions to curtail the cultivation of some crops did not, at least for the 1990-2005 period, induce a corresponding increase in the cultivation of other crops outside our analysis on the same lands. In this context it seems more likely that declines in cultivated land could have led to land sparing. By extension it seems worthwhile to pursue analyses of agricultural intensification and changes in cultivated areas.

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Table A1: Associations between Changes in Cultivated Areas for Crops across Nations, 1990-2005											
	wheat	pasture	cotto	sugar	rice	potato	coffee	corn	soy	banana	cocoa
pasture	-.026 .822										
cotton	.044 .740	.002 .984									
sugar-cane	.025 .868	-.248* .024	.021 .867								
rice	-.018 .886	-.019 .856	.033 .781	.049 .671							
potato	-.012 .902	-.021 .830	-.019 .876	.217* .069	.210* .052						
coffee	.042 .824	.374* .002	.055 .719	.121 .353	-.111 .397	-.070 .621					
corn	.056 .605	-.049 .614	.035 .758	.044 .693	.047 .644	-.022 .815	.221* .077				
soy	-.006 .962	.194 .118	.261* .048	.173 .214	.264* .031	-.034 .771	-.100 .533	.056 .625			
banana	-.060 .684	.014 .895	.561* .000	.009 .941	.159 .172	.001 .991	-.012 .924	.197* .071	.115 .430		
cocoa	.394 .106	-.055 .700	.271 .140	.043 .784	.247 .102	.106 .540	-.102 .486	.426* .003	-.020 .918	.032 .828	

Notes: the top number is the Pearson correlation coefficient; the bottom number is the p value. *p<.10.

Table A2: Changes in Areas in Specific Crops and in all Agriculture Land, 1990-2005, across Nations											
	Chnge in Past.	Chnge in Wheat	Chnge in Cotton	Chnge in Sugarca	Chnge in Rice	Chnge in Potato	Chnge in Coffee	Chnge in Corn	Chnge in Soy	Chnge in Banana	Chnge in Cocoa
Chnge in all Ag. Lands	.262* .002	-.035 .732	.242* .028	.181* .096	.207* .037	.231* .009	.335* .006	-.037 .678	.193* .087	-.024 .823	.065 .649

Notes: the top number is the Pearson correlation coefficient; the bottom number is the p value. *p<.10.

Appendix B: Countries by Region:

Sub-Saharan Africa: Angola, Benin, Burundi, Cameroon, Cape Verde, Congo - Dem Rep., Congo - Rep., Cote D'Ivoire, Djibouti, Ethiopia, Gabon, Gambia, Ghana, Guinea-Bissau, Guinea, Kenya, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe.

Near East and North Africa: Algeria, Egypt, Iran, Israel, Jordan, Lebanon, Libya, Morocco, Saudi Arabia, Syria, Tunisia, Turkey. UAE, Yemen

Europe: Albania, Austria, Belarus, Belgium, Luxembourg, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Macedonia, Malta, Moldova, Netherlands, Norway, Poland, Portugal, Romania, Serbia and Montenegro, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom

East and South Asia: Bangladesh, Brunei-Darussalam, Cambodia, India, Indonesia

China, Comoros, Japan, Korea - Dem. Rep., Korea-Rep., Laos, Malaysia, Maldives, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Timor-Leste, Viet Nam

Central Asia: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Russian Federation, Turkmenistan, Uzbekistan

Oceania: Australia, Fiji, French Polynesia, Kiribati, New Zealand, Samoa, Solomon Islands, Vanuatu,

Anglo-America: Bermuda, Canada, United States

Middle America: Antigua and Barbuda, Bahamas, Barbados, Belize, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Saint Lucia, Trinidad & Tobago,

South America: Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela

Appendix C: the Land Sparing Effects of Intensification: Determinants by Crop (Source: FAOSTAT)

	All	Corn	Rice	Soy	Wheat	Potatoes	Bananas	Cocoa	Coffee	Sugarcane	Cotton
Cons.Res. Program	.09** (.03)	-.4*** (.10)	.10* (.05)		.21** (.06)						
Production, 1990						-66** (18)			.18* (.08)		
Irrigated Land, 1990			.02 (.02)	-.07 (.07)			-.05 (.04)				
Cereal Imp.	.02* .01			.17*** (.03)			.86* (.41)	.13*** (.02)			
Prop. Land Cultivated	43** (14)	289* (130)	.73 (.54)		-292** (85)	1553*** (196)			2360*** (578)		
GDP, 1990		.12* (.06)							-.23** (.07)	-.33* (.14)	
Prop. Econ. Active Ag			42** (.12)			-1.9*** (.15)				-.70* (.29)	
SubSaharan Africa	.15* (.06)										
South America				-.58*** (.12)	.27** (.13)				.99*** (.27)	-.16* (.09)	.78*** (.17)
Cntl. Asia					-.36*** (.08)						
Adj r2	.020	.172	.099	.468	.525	.693	.066	.480	.368	.044	.203
N of Cases	927	130	102	81	101	127	85	45	63	78	80

Appendix D: Countries with Conservation Set Aside Programs during the 1990s: A list with information sources.

Countries

Austria	Italy
Belgium	Luxembourg
Canada	Netherlands
China	Portugal
Denmark	Spain
Finland	Sweden
France	Switzerland
Germany	United Kingdom
Greece	United States
Ireland	

Sources: For Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom (Common Agricultural Policy at a glance – at: http://www.epha.org/a/495); for Canada, in some provinces (Agriculture Canada – at http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1204137480722&lang=eng#e); for China (Xu et al., 2006, World Dev. 34:130-48); for Switzerland (Muller, Grether, 2001, Long run effects of the common agricultural policy for Switzerland – at: http://www.unige.ch/ses/metri/mueller/cahier0201.pdf); for United States (Osborn, 1997, Wheat and the Conservation Reserve Program, USDA, Washington, DC).