Greenhouse gas mitigation by agricultural intensification

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As efforts to mitigate climate change increase, there is a need to identify cost-effective ways to avoid emissions of greenhouse gases (GHGs). Agriculture is rightly recognized as a source of considerable emissions, with concomitant opportunities for mitigation. Although future agricultural productivity is critical, as it will shape emissions from conversion of native landscapes to food and biofuel crops, investment in agricultural research is rarely mentioned as a mitigation strategy. Here we estimate the net effect on GHG emissions of historical agricultural intensification between 1961 and 2005. We find that while emissions from factors such as fertilizer production and application have increased, the net effect of higher yields has avoided emissions of up to 161 gigatons of carbon (GtC) (590 $GtCO_2e$) since 1961. We estimate that each dollar invested in agricultural yields has resulted in 68 fewer kgC (249 $kgCO_2e$) emissions relative to 1961 technology (\$14.74/tC, or ∼\$4/tCO_2e), avoiding 3.6 GtC (13.1 $GtCO_2e$) per year. Our analysis indicates that investment in yield improvements compares favorably with other commonly proposed mitigation strategies. Further yield improvements should therefore be prominent among efforts to reduce future GHG emissions.

agriculture | greenhouse gas emissions | land use change | climate change mitigation | carbon price

Since the middle of the 20th century, global agricultural output has kept pace with a rapidly growing population, repeatedly defying Malthusian predictions of global food shortage. Between 1961 and 2005, the world's population increased by 111% (from 3.08 to 6.51 billion; Fig. 1, *Upper Left*), whereas crop production rose by 162% (from 1.8 to 4.8 billion tons; Fig. 1, *Upper Right*) (1). Although agricultural production has increased both by expanding the land area cultivated (extensification) and by improving crop yield from the land already under cultivation (intensification), the gains observed since 1961 were largely intensive. Global cropland grew by 27% (from 960 to 1,208 Mha; Fig. 1, *Lower Left*), but total crop yield increased by 135% (from 1.84 to 3.96 t/ha, weighted by production across crop groups; Fig. S1) (1). These yield gains—driven by dramatic increases in cereal and oil crops—resulted from adoption of higher-yielding crop varieties, increased use of pesticides and fertilizers (Fig. 1, *Lower Right*), and improved access to irrigation and mechanization.

From a humanitarian perspective, the agricultural intensification of the Green Revolution was a resounding success, but its environmental legacy is less clear. It has long been recognized that increased yields have spared forest and shrubland from conversion to cropland (2), but water use and chemical runoff impacted areas beyond those actually cultivated (3, 4) and abundant harvests provided the economic foundation for expanded nonagricultural land use (5). It remains a question whether modern agriculture can balance agronomy and ethics to sustain both ecological and human needs in the future (6–8). Substantial greenhouse gas (GHG) emissions from agricultural production and related land use changes further complicate this debate (9).

In 2005, agricultural production accounted for 1.4–1.7 gigatons of carbon (GtC) emissions (10–12% of total anthropogenic GHG emissions; 1 GtC = 10^9 metric tons of carbon), including 0.76 GtC equivalent N_2O and 0.90 GtC equivalent CH_4 (58% and 47% of the anthropogenic total, respectively) (10). In the same year, land use change (e.g., harvesting of forest products and clearing for agriculture) accounted for an additional 1.5 GtC emissions (11). The main components of agricultural emissions outside of land use change are N_2O released from soils related to the application of nitrogenous fertilizer (38%), CH_4 from livestock enteric fermentation, and CH_4 and N_2O from manure management (38%), CH_4 from cultivation of rice (11%), and CH_4 and N_2O from burning of savannah, forest, and agricultural residues (13%) (12). Beyond these direct emissions sources, the agricultural sector drives emissions in the industrial and energy sectors through production of fertilizers and pesticides, production and operation of farm machinery, and on-farm energy use (13).

Important mitigation potential has been identified in each of these areas (10). In particular, it has been estimated that modified rice drainage and straw incorporation practices could reduce global CH_4 emissions from rice cultivation by up to 30% (14). Precision agriculture and nutrient budgeting can facilitate more efficient use of fertilizers and thus reduce emissions associated with excess application (6). Finally, much attention has been paid to conservation tillage and the potential for sequestration of soil organic carbon in agricultural systems, which can build fertility and improve yields in degraded soils (15–21). Each of these strategies will undoubtedly play a role in any comprehensive set of crop management guidelines aimed at simultaneously mitigating agricultural GHG emissions and meeting increased future food demand, but the costs of achieving their estimated potential impacts are not well understood. It is thus instructive to compare these and other strategies to agricultural intensification, whose historical costs and impacts can be quantified.

To assess the climatic implications of agricultural intensification, we calculate agricultural GHG emissions for 1961–2005, as well as for two hypothetical "alternative world" scenarios in which growing food needs were met by land expansion (extensification) rather than yield increases (intensification). In each case, we include N_2O from agricultural soils; CH_4 from rice cultivation; C released from both biomass and soil by conversion of forest, shrub, and grassland to cropland; and N_2O, CH_4, and CO_2 from the production and use of nitrogenous, phosphate, and potash fertilizers.

In the first alternative world scenario (hereinafter AW1), we assume as a first approximation that population, the global

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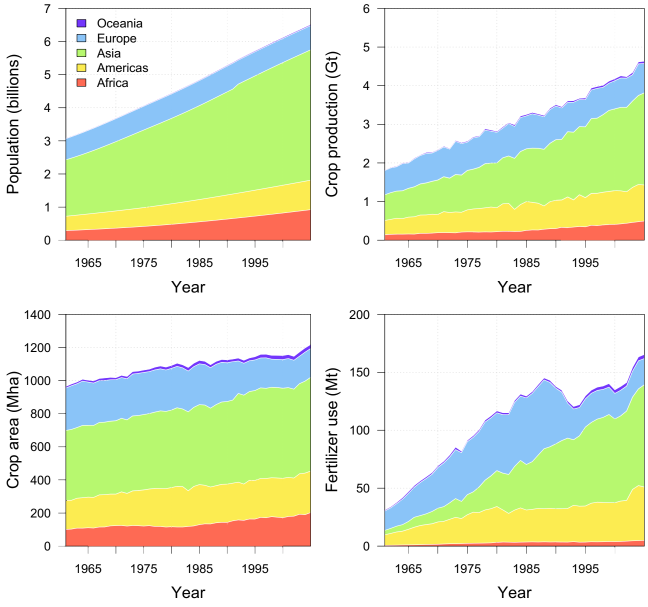

Fig. 1. Regional and global trends in population (*Upper Left*), crop production (*Upper Right*), crop area (*Lower Left*), and fertilizer use (*Lower Right*), 1961–2005.

economy, and sociopolitics evolved exactly as in the real world (hereinafter RW), but that agricultural technology and farm practices remained as they were in 1961. The AW1 scenario thus addresses the question of what it would cost, in terms of GHG impact, to replicate the current global standard of living in the absence of investment in yield improvements. Specifically, we assume the same crop yields and fertilizer application rates as in 1961, and scale land use and fertilizer production accordingly (see *Methods*). The choice of a counterfactual such as AW1 is never straightforward; for example, the AW1 scenario exogenously specifies that demand for agricultural products over time would have been identical without yield improvements, thus ignoring the role of food prices (which fell in real terms by ~40% between 1965 and 2000) (22). Previous work has explicitly modeled price effects using a partial equilibrium model to consider what might have occurred in developing countries without the Green Revolution (22, 23), although these studies do not provide details on overall investment levels or land use changes. For this study, we instead use a second hypothetical scenario in an attempt to provide a lower bound on the GHG impacts of agricultural intensification.

The second counterfactual scenario (AW2 hereinafter) is a world in which agricultural production increased only enough to maintain 1961 standards of living (in terms of per capita production) through 2005. Whereas the AW1 scenario replicates the RW evolution of living standards but meets production needs with extensive agriculture, the AW2 scenario simply maintains 1961 standards of living, again by extensification instead of intensification. This scenario thus provides a reasonable lower bound on carbon savings by projecting the 1961 per capita supply forward (i.e., maintaining 1961 living standards without the increase in supply that drove prices down in the RW). We acknowledge that a more dire lower-bound scenario exists in which increasing population (and lack of agricultural innovation) could have driven per capita consumption below 1961 levels. However, we assume that even without increased agricultural productivity, income growth from productivity gains in other sectors, as well as higher crop demand for nonfood uses, would nevertheless have kept per capita demand at 1961 levels despite any price increases; in this way, the AW2 scenario is an appropriate and realistic lower bound. To construct the AW2 scenario, we use population projections derived from pre-1961 fertility and mortality rates (24), which coincidentally result in very similar 2000 populations, albeit with different age structures (see *Methods* for a detailed explanation of the methodology).

Results

AW1 Scenario (Upper Estimates). In the AW1 scenario, an additional 1,761 Mha of cropland (an area larger than Russia) would have been needed to achieve the same production levels since 1961 while holding yields and fertilizer intensities constant, or 1,514 Mha more cropland than in the RW (Fig. 2, *Upper Left* and *Upper Center-Left*). For comparison, the amount of equivalent potential arable land available worldwide is estimated to be 2,945 Mha (25). Fertilizer use in the AW1 scenario increases from 31 Mt of nutrient to 88 Mt of nutrient, representing a constant mean annual intensity of 32 kg/ha. In the RW, total fertilizer use increased to 136 kg/ha, or 165 Mt total, although regional use varies widely (6) (Fig. 2, *Upper Center-Right* and Fig. S2). GHG emissions under the two scenarios differ significantly; Fig. 2 (*Lower Left* and *Lower Center*) shows annual agricultural GHG emissions between 1961 and 2005 for both, broken down by source. For "land conversion" emissions, we assume that cropland expansion occurred in the same proportions by biome in the AW1 scenario as in the RW, calculated as in previous studies (26). We assign biomass and soil organic carbon content values to each biome from the literature (27–29), and assume an uncertainty of ±20% in these values, reflective of regional differences (a global average of 105 ±21 tC/ha lost in conversion of land to cropland). Although decreased fertilizer use in the AW1 scenario reduces emissions from fertilizer production and agricultural soils compared with the RW, global agricultural emissions in the extensive AW1 scenario are nonetheless much greater, dominated by the effect of land use change. In sum, we find that yield gains in agriculture since 1961 have avoided emissions of 161 GtC (+104.2/−41.9 GtC), or an average of 3.6 GtC/yr (+2.3/−0.9 GtC/yr). This corresponds to 34% of the total 478 GtC emitted by humans between 1850 and 2005 (11) (Fig. S3).* A detailed explanation of the methodology is provided in *Methods*.

AW2 Scenario (Lower Estimates). The impacts of the AW2 scenario are roughly half those of the AW1 scenario. In the AW2 scenario, an additional 1111 Mha of cropland would have been needed to maintain per capita production at 1961 levels while holding yields and fertilizer intensities constant, or 864 Mha more cropland than in the RW (Fig. 2, *Upper Left* and *Upper Center-Left*). Fertilizer use in the AW2 scenario rises from 31 Mt of nutrient to 67 Mt of nutrient, representing the same constant 1961 intensity of 32 kg/ha (Fig. 2, *Upper Middle-Right* and Fig. S2). Fig. 2 (*Bottom*) shows the annual agricultural GHG emissions between 1961 and 2005 for the AW1, AW2, and RW scenarios, broken down by source and using the same methodologies. Global agricultural emissions in the AW2 scenario are also much greater than the historic RW emissions, again dominated by the effect of land use change. The AW2 scenario illustrates that, without accounting for any increases in global living standards, yield gains in agriculture since 1961 have avoided emissions of 86.5 GtC (±24.7 GtC), or an average of 1.9 GtC/yr (±0.5 GtC/yr). This corresponds to 18% of the total 478

*The asymmetric error bars for the AW1 scenario result from periods of agricultural production decreases in the RW. IPCC Tier 1 guidelines use a 1-year time frame for carbon losses (i.e., agricultural land expansion), but a 20-year time frame for carbon gains (i.e., agricultural land contraction); see *Methods* for details.

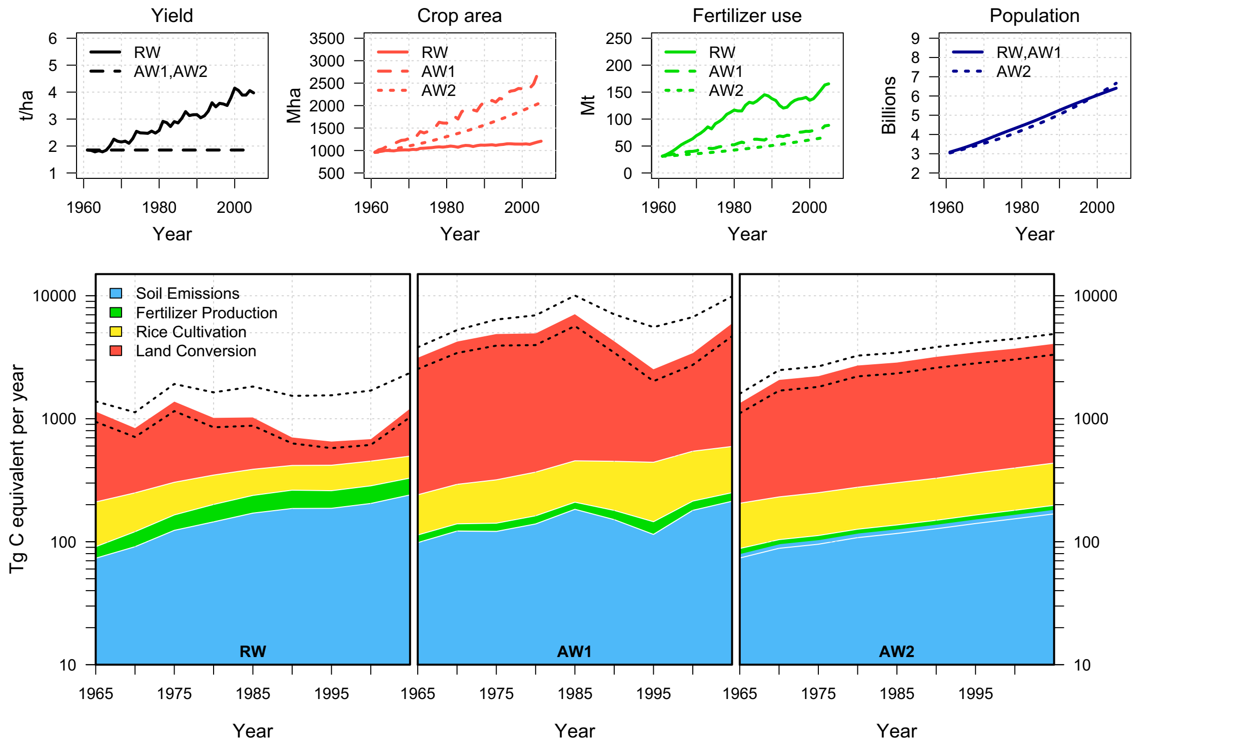

Fig. 2. Comparison of trends in the RW and AW scenarios between 1961 and 2005. (*Upper*) Agricultural yield weighted by production, cropland area, fertilizer consumption, and population. (*Lower*) Annual GHG emissions broken down by source (see *Methods*). The land use change values, plotted in green, assume the same pattern of expansion by biome in the RW and AW scenarios, corresponding to a global average of 105 ± 26 tC/ha lost, including both biomass and soil organic carbon losses.

GtC emitted by humans between 1850 and 2005 (11) (Fig. S3). A detailed explanation of the methodology is provided in *Methods*.

Cost of Carbon Savings. Assuming that yield advancements are directly related to research funding, we assess the cost-effectiveness of mitigation through yield improvements using the ratio of public and private spending on agricultural research since 1961 (30) and our AW1 and AW2 estimates of total emissions avoided through intensification. As described in *Methods*, we project where cropland expansion would have occurred in both AW scenarios; however, because it is difficult to identify both hypothetical expansion regions and the portions of agricultural investments that were relevant to yield improvements in the RW, we compute the cost-effectiveness ratio across a broad range of land carbon values and yield investment levels. Fig. 3 (*Upper*) shows the cost-effectiveness calculation for the AW1 scenario; Fig. S4 provides an equivalent plot for AW2. For the total land expansion difference between the RW and the AW scenarios (1,514 Mha for AW1, 864 Mha for AW2), any choice of average land expansion type and total yield investment value gives the effective carbon price (in \$/tC) of total avoided emissions between the AW scenarios and the RW.

For example, in a first simple estimate, we assume that the entirety of public and private investment in agriculture between 1961 and 2005 (estimated at \$1,152 billion US) contributed to yield gains achieved during that time period. Using the methodologies outlined above, we find that the average carbon content (soil + biomass) of land converted in the AW scenarios (and spared in the RW) to be ~105 tC/ha. These two values yield a carbon price for avoided emissions of \$7.16 in AW1 and \$13.32 in AW2 (per metric ton of carbon; plotted square). This method overestimates global spending on yield improvement but does not include other investments, like irrigation and fertilizer, which also contributed to yield improvements.

To refine this estimate, we narrow the range of spending to that directly relevant to yield improvements, and consider only the fraction of yield gains attributable to agricultural investment (as opposed to fertilizer, irrigation, machinery, etc.). Alston et al. (31) estimated the proportion of state agricultural research relevant for farm productivity in the United States to be between 57% and 69%. For the global case, a slightly more conservative assumption that 70% of all public and private research was relevant to yield improvements gives a cumulative 45-year total of \$806 billion in agricultural investments. Various estimates of factor productivity in agriculture estimate that research and development (R&D) accounts for around one-third of productivity growth (32–35). Attributing 34% of productivity growth (and thus carbon savings, or ∼36 tC/ha) to agricultural R&D and assuming that 70% of R&D is relevant to farm productivity gives a carbon price of \$14.74 in AW1 and \$27.43 in AW2 (per metric ton of carbon; plotted triangle). This method can be similarly used for a range of AW investment and land expansion scenarios not explored here.

The size and cost of this carbon sink (over 45 years, 3.6 +2.3/−0.9 GtC/yr for AW1 and 1.9 ± 0.5 GtC/yr for AW2) compares favorably with other proposed mitigation options available at <\$73/tC in buildings (1.49 GtC/yr), energy supply (0.49 GtC/yr), transportation (0.46 GtC/yr), and industry (0.30 GtC/yr) (Fig. 3, *Lower*) (36).

Discussion

Implications of AW Scenarios. The AW scenarios presented above do not attempt to dynamically describe what might have occurred in the absence of yield improvements; rather, they demonstrate the range of possibilities by calculating, on the one hand, the area required to support modern global living standards with 1961 yields (AW1) and, on the other hand, the area required to maintain 1961 living standards (with 1961 yields)

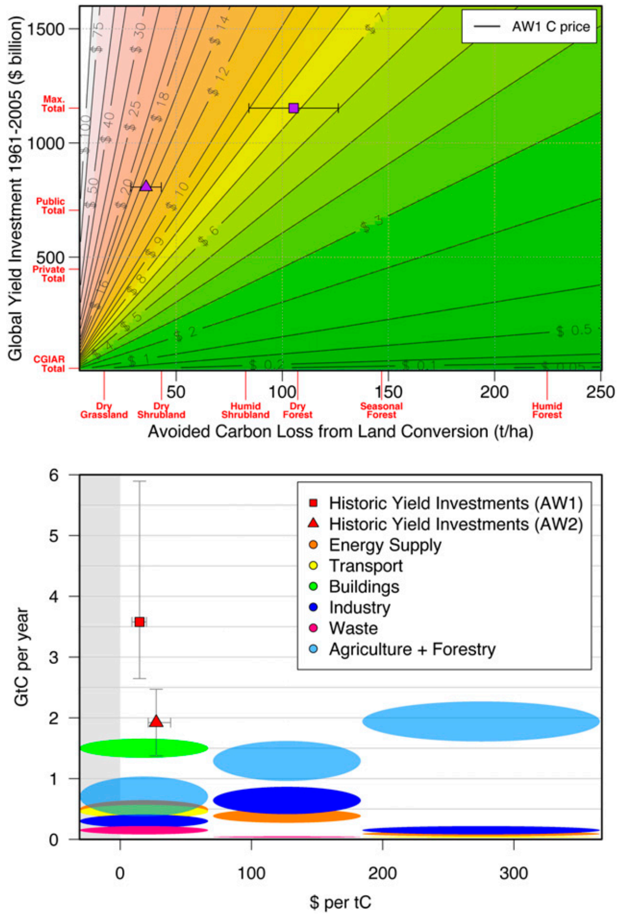

Fig. 3. (*Upper*) Price per ton of avoided carbon emissions due to investment in yield improvements for the AW1 scenario. Plotted price values are estimates for the total global agricultural investment between 1961 and 2005 divided by the total calculated carbon equivalent emissions differences between the RW and AW scenarios (including fertilizer production, agricultural soil emissions, rice production, and land use change), calculated over a broad range of land carbon values and agricultural investment estimates. Contour lines show carbon prices. The plotted square gives the price of carbon if all carbon savings between the RW and AW1 scenarios are attributed to all agricultural R&D between 1961 and 2005. The plotted triangle gives the price of carbon assuming that 70% of R&D is relevant to productivity, and that 34% of yield improvements can be attributed to R&D. Error bars span ±20% for land carbon values. (*Lower*) Cost and potential carbon savings across various sectors as calculated in the present study (red points) and by the IPCC (36).

through 2005 (AW2). Previous studies that have attempted to quantitatively model the socioeconomic impacts of international agricultural R&D have shown that without the Green Revolution's increased agricultural yields, investment and yield progress in the developed world would have increased in response to rising prices, largely offsetting the decreased production in the developed world. Nevertheless, this compensation would have been incomplete (with overall calorie consumption 14% lower in the developing world than in reality) and inefficient (food prices would be 35–66% higher than in reality, essentially offsetting the decline in real prices from 1961 to 2005). Furthermore, international shipments of food from developed to developing countries would have increased on the order of 30%, and crop area would still have increased by 2.8–4.9% more than it did historically, with proportional increases of GHG emissions from the transport sector and land conversion (22, 23).

In the AW1 scenario, this study demonstrates the incredible environmental cost modern living standards would have exacted without yield improvements (or unprecedented humanitarian crises). Although the GHG impacts of yield improvements in the RW are lower compared with the AW2 scenario, the deepest troubles in a world like AW2 would have appeared mainly after 2000 and thus are somewhat masked in this analysis. The population projections in the AW2 scenario (1950–1955 mortality and fertility rates projected forward) result, coincidentally, in population totals similar to the RW in 2000 (24). Thus, the constant per capita production in AW2 would result in less dramatic land expansion than in AW1. However, population in AW2 would strongly diverge from the RW population after 2000, resulting in a much greater future GHG impact without gains in yield.

Conclusion. Our results demonstrate the importance of land use change emissions over direct emissions of methane and nitrous oxide from agricultural systems, and suggest that the climatic impacts of historical agricultural intensification were preferable to those of a system with lower inputs that instead expanded cropland to meet global demand for food. Enhancing crop yields is not incompatible with a reduction of agricultural inputs in many circumstances, however. To the contrary, careful and efficient management of nutrients and water by precision farming, incorporation of crop residues, and less intensive tillage are critical practices in pursuit of sustainable and increased agricultural output (3, 4, 6, 37).[†] Furthermore, it has been shown in several contexts that yield gains alone do not necessarily preclude expansion of cropland, suggesting that intensification must be coupled with conservation and development efforts (5, 8, 38–41). Nonetheless, for mitigating agriculture's future contributions to climate change, continuing improvement of crop yields is paramount.

The global population is expected to reach 8.9 billion by 2050, with food demand expected to rise by 70% (42). Even if yield gains over the next four decades are smaller than those of the previous four decades, the potential to avoid future emissions may be larger and more cost-effective than the 161 GtC of emissions avoided thus far, given that current cropland expansion often occurs in tropical forests and that the remaining forests are carbon-rich relative to many cleared forests (43).[‡] Improvement of crop yields should therefore be prominent among a portfolio of strategies to reduce global greenhouse gas emissions; in order to speed the adoption of agronomic advancements that improve crop yield, mechanisms for connecting investments in yield gains to the global carbon markets should be explored.

Methods

Cropland in the AW Scenarios. In calculating emissions for the AW scenarios, we only account for cropland, and do not include pastureland in our estimates. We calculate the land needs for the AW1 scenario using FAO production data for 1961–2005, and yield data for 1961 by crop groups [Cereals, Fiber Crops, Fruit (excl. Melons), Oilcrops, Pulses, Roots and Tubers, Vegetables & Melons] (1). For the AW2 scenario, 1961 per capita production by crop groups is projected forward to 2005 using the AW2 population projections, which are derived assuming 1950–1955 fertility and mortality rates (24). We do not explicitly calculate emissions for livestock, burning of agricultural residues, pesticide and fuel use, agricultural machinery, or irrigation in the RW and AW scenarios, but discuss assumptions and potential differences in these sectors below.

Additional Assumptions for the AW1 Scenario. We assume that livestock populations are the same in the RW and AW1, because total food and feed production do not change, and thus emissions due to enteric fermentation,

[†]Although our analysis focuses on the GHG emissions of intensification and extensification, each has additional important environmental consequences, such as the loss of fertilizers and pesticides into surrounding ecosystems from intensive systems or the biodiversity loss associated with land use change in extensive systems.

[‡]Furthermore, our estimates for emissions from land use change exclude pasture land and areas dedicated to biofuels, and neglect the projected increase in dietary preference for meat as per capita GDP grows.

manure management, and land conversion to grazing land are identical in both scenarios. Similarly, we assume that burning of agricultural residues is the same in both cases (because total production is the same). Finally, we do not include any pesticides or fuel use in our analysis, nor do we account for any transport of food in the AW1 scenario. (Food would be harvested and distributed from a more extensive land base in AW1.) Between 1961 and 2005, the number of agricultural tractors in use worldwide rose from 11.3 million to 28.5 million, an increase of 153%. Similarly, the irrigated area increased from 139 Mha to 284 Mha, a gain of 104% (1). Nonetheless, for both machinery and irrigation, an assumption of constant intensity in the AW (constant number of machines per area and constant percentage of area irrigated) would have resulted in greater emissions from machinery production and irrigation in the AW1. Thus, we conservatively assume that machinery use and irrigation area remained the same in AW1 and RW.

Additional Assumptions for the AW2 Scenario. Unlike in the AW1 scenario, livestock numbers are lower in the AW2 scenario (assuming constant per capita production at 1961 levels) than in the RW. Total RW annual livestock-related GHG emissions in 2004 (including feed production, farm operations, enteric fermentation, manure management, and soil emissions from pasture land and feed crops) have been estimated as ∼1.94 GtC/yr equivalent (∼7.1 $GtCO_2e$/yr), of which ∼0.68 GtC/yr equivalent (∼2.5 $GtCO_2e$/yr) is from land use changes (44). Extensive systems contributed 70% of these emissions (44); thus, a conservative estimate that the AW2 scenario included no intensive livestock operations results in a savings of up to ∼0.58 GtC/yr (∼2.1 $GtCO_2e$/yr) in the livestock sector compared with the RW.

Emissions due to burning of agricultural residues can be conservatively assumed to be 15% lower in AW2 than RW (the difference in total production), although we do not calculate burning emissions for the RW. As in the AW1 scenario, we do not include any pesticides, fuel use, or transport in the AW2 calculations. An assumption of constant intensity for machinery and irrigation results in 5% more irrigated land and 17% fewer agricultural tractors in the AW2 scenario compared with the RW.

Emissions Due to Conversion of Land to Cropland. To calculate emissions from the conversion of land to cropland in the RW, we first determine the expansion patterns by biome, following a method outlined previously (26). We overlay the Historical Croplands Dataset, 1700–1992 (0.5 degree; described in ref. 26) with the Global Potential Vegetation Dataset (0.5 degree; described in ref. 26) to estimate the percentage of cropland expansion occurring in each major biome for each year between 1961 and 1992. We follow the same procedure using the *Agricultural Lands in the Year 2000* dataset (5minute, described in ref. 45), and the 5minute version of the *Global Potential Vegetation Dataset,* and use these biome percentages from the year 2000 for the 1993–2005 period. These percentages are presented in Table S1 for reference.

Calculating carbon emissions due to land conversion is difficult because of large variations and uncertainties in biomass and soil carbon, as well as in sensitivity to the method of carbon accounting (reviewed and described in ref. 46). We assign biomass and soil carbon values to each biome (largely from refs. 27–29) and assume an uncertainty of ±20%, reflective of regional variations. Table S2 summarizes the values used in our calculations, with sources.

We follow Gibbs et al. (27) and the 2006 Intergovernmental Panel on Climate Change (IPCC) Tier 1 GHG emissions calculations guidelines (47) and assume that carbon losses from land converted to cropland occur over 1 year and that carbon sequestration in abandoned cropland occurs over 20 years. We assume 70% of land converted to cropland is for crops, and 30% for tree plantations based on FAO trends (1), and that land converted for crops results in loss of 25% of soil carbon, and land converted to plantations results in loss of 10% of soil carbon. Finally, for land converted to cropland, we assign a new biomass carbon value of 1/2 the peak carbon content of the crop, assuming global average peak values of 5 t/ha for crops, 77 t/ha for oil crop plantations, and 34 t/ha for fruit (Table S2).

For the AW scenarios, we calculate emissions as follows for the baseline comparison plotted in Figs. 2 and 3, and presented in Figs. S3 and S4. We assume that land expansion occurred across different biomes at the same percentages as in the RW, and we assume the same uncertainty of ±20% for carbon values. These baseline AW land and soil carbon content assumptions correspond to a global average of 105 ± 21 tC/ha lost (total, including both biomass and soil carbon losses) in the conversion of other types of land to cropland. Cumulative emissions from the RW and AW scenarios are plotted in Fig. S3.

Soil Organic Carbon Content Over Time. We assume that after a conversion to agricultural land, soil organic carbon content remains the same in the RW and AW scenarios. Although management practices, such as conservation tillage, can increase soil organic carbon content in both extensive and intensive systems (15, 16), we do not assume any such gains in the AW scenarios between 1961 and 2005.

Emissions From Fertilizer Production. To estimate emissions due to production of fertilizers used in a given year, we apply the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model emissions factors for nitrogen, phosphate, and potash fertilizers (48) to total fertilizer consumption data. We assume fertilizer application rates remain at 1961 levels in both AW scenarios, and scale fertilizer consumption and associated production emissions accordingly.

Emissions From Agricultural Soils. To calculate emissions from agricultural soils, we follow IPCC Tier 1 GHG inventory guidelines by crop group (47). Our estimates agree with those reported previously (12, 49, 50).

Rice Cultivation. As with total cropland, we calculate the amount of land that would be needed to meet RW production values with 1961 yields. We follow the methodology outlined by Yan (14, 51) to calculate methane emissions from rice cultivation and GHGs from the burning of rice straw. For both AW expansion scenarios, we assume that the percentages of rain-fed and irrigated systems are the same as in the RW, and that drainage practices and organic amendments are the same in each scenario. These values are derived following the methods and sources used by Yan et al. (14, 51–53).

Carbon Price Calculation. We estimate global total public and private agricultural investment values for 1961–2005 from (30). We use the values for public research spending in 1981, 1991, and 2000, and use the same public funding percentage for developing and developed world to estimate total spending in each time period. We assume a growth rate of 4.5% in spending between 1961–1981, and use the 1981 value to extrapolate back in time; we assume a linear increase from 1981 to 2000; and we estimate the values for 2001–2005 assuming a 2.1% annual growth in agricultural investment (30).

For a different perspective on the estimates presented in the paper, we perform a simple cost-benefit analysis and calculate the percentage of historic yield improvement that would have to be due to agricultural investment to break even, for a given carbon price. We use the baseline AW land carbon content assumptions described above, which correspond to a global average of 105 ± 21 tC/ha lost (total, including both biomass and soil carbon losses) in conversion of other types of land to cropland. This calculation is shown in Fig. S5 for both AW1 (*Upper*) and AW2 (*Lower*). Although carbon savings are not the only benefit of agricultural intensification, this analysis can be used to give an upper bound on the value of carbon savings due to agricultural investment.

Irrigation Investment. We do not include investment in irrigation infrastructure in our price calculation, nor do we make assumptions about irrigation investment in either AW scenario. However, it is worth noting that, between 1961–2005, global total area equipped for irrigation increased from 139 Mha to 284 Mha, with 75% of this change in Asia (19% in the Americas and Europe, 4% in Africa, and 1% in Oceania). Cost estimates for irrigation investments vary by region (54); using a value of $2,000 per ha gives a total cost of $310 billion, or just under 27% of the maximum global total agricultural investment.

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