Resource-Conserving Agriculture Increases Yields in Developing Countries

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Despite great recent progress, hunger and poverty remain widespread and agriculturally driven environmental damage is widely prevalent. The idea of agricultural sustainability centers on the need to develop technologies and practices that do not have adverse effects on environmental goods and services, and that lead to improvements in food productivity. Here we show the extent to which 286 recent interventions in 57 poor countries covering 37 M ha (3% of the cultivated area in developing countries) have increased productivity on 12.6 M farms while improving the supply of critical environmental services. The average crop yield increase was 79% (geometric mean 64%). All crops showed water use efficiency gains, with the highest improvement in rainfed crops. Potential carbon sequestered amounted to an average of 0.35 t C ha^{-1} y^{-1}. If a quarter of the total area under these farming systems adopted sustainability enhancing practices, we estimate global sequestration could be 0.1 Gt C y^{-1}. Of projects with pesticide data, 77% resulted in a decline in pesticide use by 71% while yields grew by 42%. Although it is uncertain whether these approaches can meet future food needs, there are grounds for cautious optimism, particularly as poor farm households benefit more from their adoption.

Introduction

What is the best way to increase agricultural productivity in developing countries that still, despite efforts over several decades, have some 800 million people short of food? The question is controversial, with widely varying positions about the types of inputs and technologies likely to be effective (*1−4*). Great technological progress in the past half century has not been reflected in major reductions in hunger and poverty in developing countries.

However, many novel initiatives have emerged that are demonstrating that agriculture in poor countries can be greatly improved. Here we evaluate how farmers in 286 projects in 57 countries have improved food crop productivity since the early to mid 1990s, and at the same time increased both water use efficiency and carbon sequestration, and reduced pesticide use. These initiatives also offer the prospects of resource conserving agriculture both reducing adverse effects on the environment and contributing to important environmental goods and services (e.g., climate change mitigation).

In the past 40 years, per capita world food production has grown by 17%, with average per capita food consumption in 2003 of 2780 kcal day^{-1} (*5*), where a majority of the chronically hungry are small farmers who produce much of what they eat. Yet consumption in 33 poor countries is still less than 2200 kcal day^{-1}. Food demand will both grow and shift in the coming decades, as (i) population growth increases absolute demand for food; (ii) economic growth increases people's purchasing power; (iii) growing urbanization encourages people to adopt new diets; and (iv) climate change threatens both land and water resources.

Increased food supply is a necessary though not sufficient condition for eliminating hunger and poverty. What is important is who produces the food, has access to the technology and knowledge to produce it, and has the purchasing power to acquire it. The great success of industrialized agriculture in recent decades has masked significant negative externalities, with environmental and health problems increasingly well-documented and costed, including in Ecuador, China, Germany, the Philippines, U.K. and United States (*6−11*). There are also growing concerns that such systems may not reduce food poverty. Poor farmers need low-cost and readily available technologies and practices to increase local food production and to raise their income. At the same time, land and water degradation is increasingly posing a threat to food security and the livelihoods of rural people who often live on degradation-prone lands (*12*).

The idea of agricultural sustainability centers on food production that makes the best use of nature's goods and services while not damaging these assets. Many different terms have come to be used to imply greater sustainability in some agricultural systems over prevailing ones (both pre-industrial and industrialized) (*13*). Agricultural sustainability in all cases, however, emphasizes the potential benefits that arise from making the best use of both good genotypes of crops and animals and their ecological management. Agricultural sustainability does not, therefore, mean ruling out any technologies or practices on ideological grounds (e.g., genetically modified crop, organic practice)—provided they improve productivity for farmers, and do not harm the environment (*12−16*).

In this research, we concentrate on projects that have made use of a variety of packages of resource-conserving technologies and practices. These include the following: (1) *Integrated pest management*, which uses ecosystem resilience and diversity for pest, disease, and weed control, and seeks only to use pesticides when other options are ineffective. (2) *Integrated nutrient management*, which seeks both to balance

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TABLE 1. Summary of FAO—World Bank Farming System Categories in Developing Regions and Number of Project Entries for This Study[a]

FAO farm system category	number of subsystems	land area (M ha)	cultivated area (M ha)	agricultural population (M)	agricultural population per cultivated hectare	no. project entries for each category
1. smallholder irrigated	1	219	15	30	2.0	16
2. wetland rice	3	330	155	860	5.5	55
3. smallholder rainfed humid	11	2013	160	400	2.5	95
4. smallholder rainfed highland	10	842	150	520	3.5	40
5. smallholder rainfed dry/cold	19	3478	231	490	2.1	43
6. dualistic mixed	16	3116	414	190	0.5	20
7. coastal artisanal	4	70	11	60	5.5	2
8. urban-based and kitchen garden	6	na	na	40	na	15
total	72	10068	1136	2590	2.28	286

[a] From Dixon and Gulliver (*19*); na = not available.

the need to fix nitrogen within farm systems with the need to import inorganic and organic sources of nutrients, and to reduce nutrient losses through erosion control. (3) *Conservation tillage*, which reduces the amount of tillage, sometimes to zero, so that soil can be conserved and available moisture used more efficiently. (4) *Agroforestry,* which incorporates multifunctional trees into agricultural systems, and collective management of nearby forest resources. (5) *Aquaculture*, which incorporates fish, shrimps, and other aquatic resources into farm systems, such as into irrigated rice fields and fish ponds, and so leads to increases in protein production. (6) *Water harvesting* in dryland areas, which can mean formerly abandoned and degraded lands can be cultivated, and additional crops can be grown on small patches of irrigated land owing to better rainwater retention. (7) *Livestock integration* into farming systems, such as dairy cattle and poultry, including using zero-grazing.

Here we show the extent to which recent successful interventions focusing on agricultural sustainability (sometimes called bright spots (*17*)) have increased total food crop productivity in developing regions. Our questions are as follows: (i) To what extent can farmers increase per hectare and per farm food production by using low-cost and locally available technologies and inputs? (ii) What impacts do such methods have on environmental goods and services (in particular using the water use efficiency, carbon sequestration, and pesticide use as proxies to indicate changes in adverse effects on the environment)?

Methodology

We used both questionnaires and published reports by projects to assess adoption of sustainable agriculture and changes over time. As in earlier research (*18*), data were triangulated from several sources, and cross-checked by external reviewers and regional experts. This study involves analysis of projects sampled once in time ($n = 218$) and those sampled twice over a 4 year period to assess temporal changes ($n = 68$). Not all proposed cases were accepted for the dataset, and rejections were based on a strict set of criteria (*18*). As this was a purposive sample of "best practice" initiatives, the findings are not representative of all farms in developing countries.

We used a novel typology of farming systems developed by FAO for the World Bank to classify these projects (*19*) into 8 broad categories based on the following social, economic, and biophysical criteria: (i) the available natural resource base, including water, land, grazing areas, and forest; climate and altitude; landscape, including slope; farm size, tenure, and organizations; and access to services including markets; and (ii) the dominant patterns of farm activities and household livelihoods, including field crops, livestock, trees, aquaculture, hunting and gathering, processing, and off-farm activities; and the main technologies used, which determine the intensity of production and integration of crops, livestock and other activities.

Table 1 contains a summary of the global land area and population located in these eight major farm system categories. On average, these sustain 2.28 people per cultivated hectare of land (range 0.5−5.5). A total of 72 farming subsystems have been identified across the developing regions, some of which comprised similar systems occurring on different continents (e.g., wetland rice systems in East Asia/Pacific and in South Asia). A summary of all these systems and their locations is contained in the Supporting Information. In our study, system categories 2−5 are well-represented, with 40−95 projects in each. System categories 1, 6, and 8 have 15−20 projects each, and category 7 has only two.

Extent of Agricultural Sustainability and Impacts on Yields. Table 2 contains a summary of the location and extent of the 286 agricultural sustainability projects across the eight categories of farming systems in 57 countries. In all, some 12.6 million (M) farmers on 37 M ha were engaged in transitions toward agricultural sustainability in these 286 projects. This is just over 3% of the total cultivated area shown in Table 1. The largest number of farmers was in wetland rice-based systems, mainly in Asia (category 2), and the largest area was in dualistic mixed systems, mainly in southern Latin America (category 6).

We were able to show that agricultural sustainability is spreading to more farmers and hectares. In the 68 randomly re-sampled projects from the original study, there was a 56% increase over the 4 years in the number of farmers (from 5.3 to 8.3 M), and 45% in the number of hectares (from 12.6 to 18.3 M). These resurveyed projects comprised 60% of the farmers and 44% of the hectares in the original sample of 208 projects (*18*). In the earlier study, we reported that 89 projects for which there was reliable yield data showed increases in per hectare food production.

For the 360 reliable yield comparisons from 198 projects that we now have, the mean relative increase was 79% across the very wide variety of systems and crop types (see Table B in the Supporting Information for full details of changes in each farming system category). However, there was a wide spread in results (Figure 1). While 25% of projects reported relative yields >2.0, (i.e., 100% increase), half of all the projects had yield increases of between 18% and 100%. The geometric mean is a better indicator of the average for such data with a positive skew, but this still shows a 64% increase in yield. However, the average hides large and statistically significant differences among the main crops (Figures 2 and 3). In nearly all cases there was an increase in yield with the project. Only in rice were there 3 reports where yields decreased, and the increase in rice was the lowest (mean = 1.35), although it

TABLE 2. Summary of Adoption and Impact of Agricultural Sustainability Technologies and Practices on 286 Projects in 57 Countries[a]

FAO farm system category	number of farmers adopting	number of hectares under sustainable agriculture	average % increase in crop yields
1. smallholder irrigated	177,287	357,940	129.8 (±21.5)
2. wetland rice	8,711,236	7,007,564	22.3 (±2.8)
3. smallholder rainfed humid	1,704,958	1,081,071	102.2 (±9.0)
4. smallholder rainfed highland	401,699	725,535	107.3 (±14.7)
5. smallholder rainfed dry/cold	604,804	737,896	99.2 (±12.5)
6. dualistic mixed	537,311	26,846,750	76.5 (±12.6)
7. coastal artisanal	220,000	160,000	62.0 (±20.0)
8. urban-based and kitchen garden	207,479	36,147	146.0 (±32.9)
all projects	12,564,774	36,952,903	79.2 (±4.5)

[a] Yield data from 360 crop project combinations; reported as % increase (thus a 100% increase is a doubling of yields). Standard errors are given in brackets.

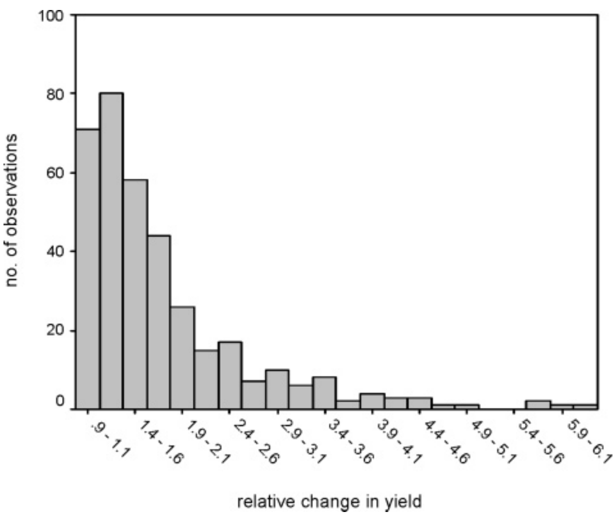

FIGURE 1. Histogram of change in crop yield after or with project, compared to before or without project ($n = 360$, mean = 1.79, SD 0.91, median = 1.50, geometric mean = 1.64).

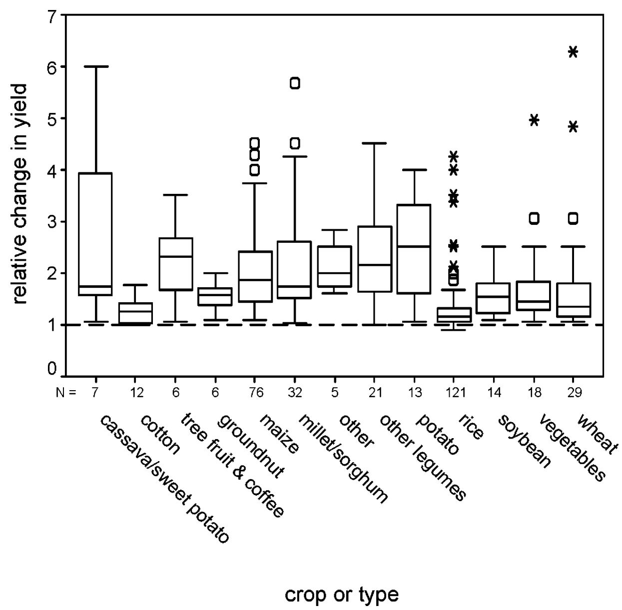

FIGURE 2. Box and whisker plot of change in crop yield after or with project, compared to before or without project. Bold lines within boxes indicate median value, box limits indicate interquartile range (i.e., 50% of values lie within the box), whiskers indicate highest and lowest, excluding outliers (○, 1.5−3 × box length distance away from edge of box) or extremes (*, >3 × box length). "Other" group consists of sugar cane ($n = 2$), quinoa (1), oats (2).

constituted a third of all the crop data. Cotton showed a similarly small mean yield increase.

The mean (2.84) and spread was largest in cassava and sweet potato crops, although the sample is small. Soybean and groundnut showed mean increases of about 50%. Maize, millet and sorghum, potatoes, and the other legumes group (beans, pigeon peas, cowpea, chickpea) all showed mean yield increases of >100%, significantly higher than those for cotton, rice, and groundnut ($P < 0.05$). For most of the main field crops that are well represented in the survey, those with low yields before intervention often showed larger relative improvements, either because of growth limiting environments, or perhaps reduced investment in developing these crops, although potato showed large increases across the range (Figure 4).

Though many technologies and practices were used in these projects, three types of technical improvement are likely to have played substantial roles in food production increases: (i) more efficient water use in both dryland and irrigated farming; (ii) improvements in organic matter accumulation in soils and carbon sequestration; and (iii) pest, weed, and disease control emphasizing in-field biodiversity and reduced pesticide (insecticide, herbicide, and fungicide) use.

Impacts on Farm Water Use Efficiency. Widespread appreciation of the "global water crisis" recognizes that scarcity of clean water is affecting food production and conservation of ecosystems. By 2025 it is predicted that most developing countries will face either physical or economic water scarcity (*20*). Water diverted from rivers increased 6-fold between 1900 and 1995 (*21*), far outpacing population growth. Increasing demand for freshwater now threatens the integrity of many aquatic ecosystems, and their associated environmental services (*22*). As agriculture accounts for 70% of current water withdrawals from rivers, improving the productivity of water use in agriculture is a growing challenge.

The potential for increasing food production while maintaining water-related ecosystem services rests on capacity to increase water productivity (WP), i.e., by realizing more kg of food per unit of water. Sustainable agricultural practices may do this by (i) removing limitations on productivity by enhancing soil fertility; (ii) reducing soil evaporation through conservation tillage; (iii) using more water-efficient varieties; (iv) reducing water losses to unrecoverable sinks; (v) boosting productivity by supplemental irrigation in rainfed systems; and (vi) inducing microclimatic changes to reduce crop water requirements (*23*). We calculated changes in WP for field crops in 144 projects from the data set (Table 3) based on reported crop yields and average potential evapotranspiration (ETp), for each project location during the relevant growing season. Actual evapo-

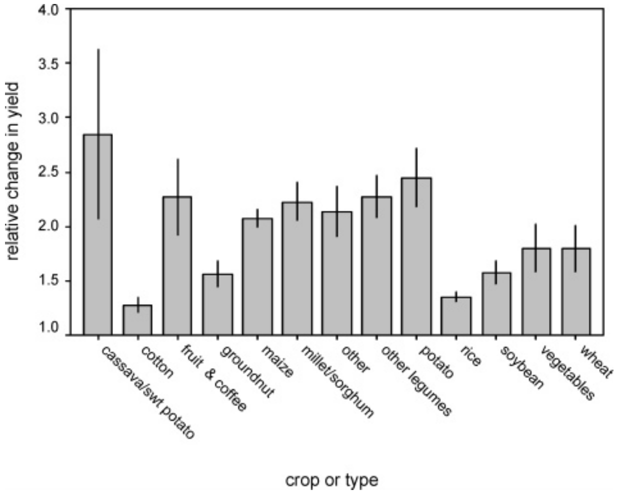

FIGURE 3. Mean changes in crop yield after or with project, compared with before or without project. Vertical lines indicate ± SEM. "Other" group consists of sugar cane ($n = 2$), quinoa (1), oats (2).

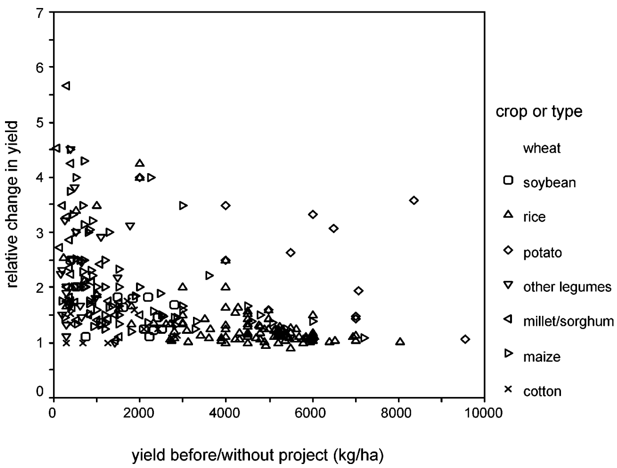

FIGURE 4. Relationship between relative changes in crop yield after (or with project) to yield before (or without project). Only field crops with $n > 9$ shown.

transpiration (ETa) was assumed to equal 80% of ETp, and ETa to remain a constant at different levels of productivity.

WP gains were high in rainfed systems, and moderate in irrigated systems, and were in agreement with other studies reporting ranges of WP (*23*). The very large increase for the vegetables and fruits is probably an overestimate as we did not adjust ETp for new crops or lengthened cropping periods. Variability was high due to the wide variety of practices represented in the dataset, but do indicate that gains in WP are possible through adoption of sustainable farming technologies in a variety of crops and farm systems. Our results, and others (*24*−*25*), demonstrate that the greatest opportunity for improvement in water productivity is in rainfed agriculture. Better farm management, including supplemental irrigation and fertility management can significantly reduce uncertainty, and thus avoid chronic low productivity and crop failure that are characteristic of many rainfed systems.

Impacts on Carbon Sequestration. The 1997 Kyoto Protocol to the UN Framework Convention on Climate Change established an international policy context for the reduction of carbon emissions and increases in carbon sinks to address the global challenge of anthropogenic interference with the climate system. It is clear that both emission reductions and sink growth will be necessary for mitigation of current climate change trends (*26*−*28*). Carbon sequestration is defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere (*29*).

One of the actions farmers can take is to increase carbon sinks in soil organic matter and above-ground biomass. We calculated the potential annual contributions being made in these 286 projects to carbon sink increases in soils and trees, using established carbon audit methods (*30*) (Table 4). As the focus is on what sustainable methods can do to increase quantities of soil and above-ground carbon, we did not take account of existing stocks of carbon. Soil carbon sequestration is corrected for climate, as rates are higher in humid compared with dry zones, and generally higher in temperate than tropical areas (*28*−*29*).

These projects were potentially sequestering 11.4 Mt C y^{-1} on 37 M ha. If scaled up, assuming that 25% of the areas under the different farming system categories globally (Table 1) adopted these same sustainability initiatives, this would result in sequestration of 100 (±4) Mt C y^{-1} The average gain was 0.35 t C ha^{-1} y^{-1}, and an average per household gain of 0.91 t C y^{-1}. The per hectare gains vary from 0.15 t C ha^{-1} y^{-1} for smallholder irrigated systems (category 1) to 0.46 t C ha^{-1} y^{-1} for category 3 systems. For most systems, per households gains were in the range 0.05−0.5 t C y^{-1}, with the much larger farms of southern Latin America using zero-tillage achieving the most at 14.9 t C y^{-1}. Such gains in carbon may offer new opportunities to households for income generation under emerging carbon trading schemes.

Impacts on Pesticide Use. Integrated pest management (IPM) programs are beginning to show how pesticide use can be reduced and modified without yield penalties in a variety of farm systems, such as in irrigated rice in Asia (*31*) and rainfed maize in Africa (*32*). In principle, there are four possible trajectories an agricultural system can take if IPM is introduced: (i) both pesticide use and yields increase (A); (ii) pesticide use increases but yields decline (B); (iii) both pesticide use and yields fall (C); or (iv) pesticide use declines, but yields increase (D).

The conventional wisdom is that pesticide use and yields are positively correlated, and so only trajectories moving into A and C are likely (*33*−*34*). A change into sector B would be against economic rationale, as farmers' profits would invariably fall and behavior change. A shift into sector D would indicate that current pesticide use has negative yield effects. This could be possible with excessive use of herbicides or when pesticides cause outbreaks of secondary pests (*35*). We analyzed the 62 IPM initiatives in 21 developing countries in the dataset (Figure 5). The evidence on pesticide use is derived from data on both the number of sprays per hectare and the amount of active ingredient per hectare. There is only one case in sector B reported in recent literature (*36*), and so this was not included.

Sector A contains 10 projects where pesticide use increased. These are mainly in zero-tillage and conservation agriculture systems, where reduced tillage creates benefits for soil health and reduces off-site pollution and flooding costs. These systems usually require increased use of herbicides for weed control (*37*), though there are examples of organic zero-tillage systems (*38*). The 5 cases in sector C show a 4.2% (±5.0) decline in yields with a 93.3% (±6.7) fall in pesticide use. Most cases, however, are in category D where pesticide use declined by 70.8% (±3.9) and yields increased by 41.6% (±10.5). While pesticide reduction is to be expected, as farmers substitute pesticides by information, the cause of yield increases induced by IPM are complex. It is likely that farmers who receive good quality field training will not only improve their pest management skills but also become more efficient in other agronomic and ecological management practices. They are also likely to invest cash saved from

TABLE 3. Summary of Changes in Water Productivity by Major Crop Type Arising from Adoption of Sustainable Agricultural Technologies and Practices in 144 Projects[a]

crop	water productivity before intervention (kg food m^{-3} water ETa)	water productivity after intervention (kg food m^{-3} water ETa)	water productivity gain (kg food m^{-3} water ETa)	% increase in WP
irrigated				
rice (n =18)	1.03 (±0.22)	1.19 (±0.12)	0.16 (±0.04)	15.5%
cotton (n = 8)	0.17 (±0.04)	0.22 (±0.05)	0.05 (±0.02)	29.4%
rainfed				
cereals (n = 80)	0.47 (±0.06)	0.80 (±0.09)	0.33 (±0.05)	70.2%
legumes (n=19)	0.43 (±0.07)	0.87 (±0.16)	0.44 (±0.11)	102.3%
roots and tubers (n=14)	2.79 (±0.73)	5.79 (±1.08)	3.00 (±0.65)	107.5%
urban and kitchen gardens				
vegetables and fruits (n=5)	0.83 (±0.29)	2.96 (±0.97)	2.13 (±0.71)	256.6%

[a] Standard errors in brackets.

TABLE 4. Summary of Potential Carbon Sequestered in Soils and Above-Ground Biomass in the 286 Projects[a]

FAO farm system category	carbon sequestered per hectare (t C ha^{-1} y^{-1})	total carbon sequestered (Mt C y^{-1})	carbon sequestered per household (t C y^{-1})
1. smallholder irrigated	0.15 (±0.012)	0.011	0.06
2. wetland rice	0.34 (±0.035)	2.53	0.29
3. smallholder rainfed humid	0.46 (±0.034)	0.34	0.20
4. smallholder rainfed highland	0.36 (±0.022)	0.23	0.56
5. smallholder rainfed dry/cold	0.26 (±0.035)	0.20	0.32
6. dualistic mixed	0.32 (±0.023)	8.03	14.95
7. coastal artisanal	0.20 (±0.001)	0.032	0.15
8. urban-based and kitchen garden	0.24 (±0.061)	0.015	0.07
total	0.35 (±0.016)	11.38	0.91

[a] Standard errors in brackets.

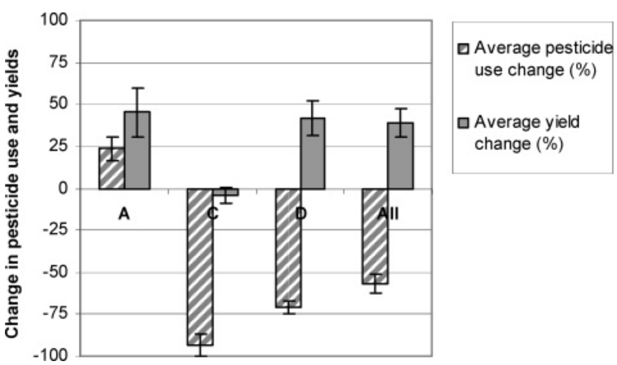

FIGURE 5. Changes in pesticide use and yields in 62 projects (A, n = 10; C, n = 5; D, n = 47).

pesticides in other inputs such as higher quality seeds and fertilizers. This analysis indicates considerable potential for avoiding environmental costs.

Discussion

It is uncertain whether progress toward agricultural sustainability, delivering benefits at the scale occurring in these projects, will result in enough food to meet the future food needs in developing countries after continued population growth, urbanization, and the dietary transition to meat-rich diets (*39*). Even the substantial increases reported here may not be enough. However, more widespread adoption of these resource conserving technologies, combined with other innovations in crop and livestock genotypes, would contribute to increased agricultural productivity (*1, 16*), particularly as evidence indicates that productivity can grow in many farming systems as natural, social, and human capital assets also grow (*40*). Our findings also show that poor households benefit substantially.

But improving agricultural sustainability alone will not solve all food poverty problems. The challenge is to find ways to improve all farmers' access to productive technologies and practices that are also resource conserving. The critical priority is now international, national, and local policy and institutional reforms (*41*) designed to benefit both food security and income growth at national and households levels, while improving the supply of critical technologies that improve the supply of environmental goods and services.

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Supporting Information Available

Table A1 containing full details of the classification system developed by FAO (Dixon and Gulliver, ref *19*) for farming systems. This separates farming systems into 8 types (irrigated; wetland rice based; smallholder rainfed humid; smallholder rainfed highland; smallholder rainfed dry/cold; dualistic; coastal artisanal fishing; urban-based) for six regions of the world (Sub-Saharan Africa; Middle East and North Africa; Europe and Central Asia; South Asia; East Asia and Pacific; Latin America and Caribbean). Table A2 summarizing the location of the 286 projects in this study in these farming systems types, and giving the impact of agricultural sustainability in each farming system. Part C containing profiles of 47 of the 286 projects (11 in Latin America, 17 in Africa, and 19 in Asia) as examples of how the technologies were adopted and their environmental and social outcomes. This material is available free of charge via the Internet at http://pubs.acs.org.

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