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Estimating the Global Investment Gap in Research and Innovation for Sustainable Agriculture Intensification in the Global South

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International Food Policy Research Institute

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Executive summary

An investment gap stands in the way of sustainable agriculture intensification

Sustainable food production needs to increase if it is to meet the rising and evolving food demands caused by growing populations, increasing incomes and urbanization. However, it faces numerous challenges. Competition for water resources is increasing – not only between people and the natural environment, but between cities and rural areas as well. Overuse of water due to wasteful irrigation management is worsening water scarcity. Climate change is bringing higher temperatures and changing precipitation patterns, as well as a higher likelihood of increased weather variability and extreme events. At the same time, agriculture is a major contributor to greenhouse gas (GHG) emissions, so sustainable agriculture intensification also needs to address climate change by reducing GHG emissions and sequestering carbon.

These challenges can be addressed through investments in innovation for sustainable agriculture intensification. Such investments in the Global South have the potential to achieve key ambitions of the Sustainable Development Goals (SDGs) and the Paris Agreement on climate change. To do that, however, an investment gap will have to be filled.

The investment gap is clear and measurable

This report estimates the size of the gap, and calculates the additional research and innovation investments in the Global South that could bring hunger close to zero by 2030, in line with SDG2; reduce GHG emissions from the agricultural sector, in line with SDG13 and consistent with a 2°C climate trajectory; and improve efficiency of water use and reduce agricultural water pollution, making progress toward SDG6.

Innovation for sustainable agriculture intensification is defined here as the creation, development and implementation of new technologies, policies, techniques and management practices for sustainable productivity growth, climate change mitigation and water resource improvement that drive progress toward the SDG targets and 2°C climate trajectory.

The first part of this report uses an International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) scenario methodology to estimate the public and private investments in agricultural research and development (R&D) that could reduce the share of population at risk of hunger below 5% by 2030. This analysis measures the outcomes of these investments against a reference scenario of business as usual that incorporates the impacts of climate change. In addition to this modeling , an analysis of technical options for additional GHG mitigation draws on evidence in the literature regarding potential impacts, costs and adoption rates of climate smart techniques and management practices. We also model the investment in innovative water resource management that will achieve substantial reductions in water use by 2030.

Investments can accelerate the end of hunger

Increased investments in agricultural R&D – by CGIAR, national agricultural research systems and the private sector – would, together with investments that raise research efficiency, reach the SDG2 hunger target in East Asia, South Asia and Latin American and the Caribbean. This is an impressive achievement in the short time remaining until 2030. Sub-Saharan Africa would remain well above the target with 11.8% at risk of hunger in 2030, although this is still a major improvement relative to the 24.3% share who were hungry in 2010. This investment scenario requires an additional USD 4 billion per year above the reference scenario, an increase of 41% compared to the reference scenario investments. The private sector would account for 13% of the additional investments.

These investments would adapt agriculture to climate change by erasing its effect on hunger seen in the reference scenario. In fact, this adaptation is achieved by the USD 2.1 billion international public component alone, which prevents climate change from pushing 66 million more people into risk of hunger by 2030. By 2030, the investments would also raise incomes by 2% and gross domestic product by USD 1.7 trillion in the Global South. They would also reduce global food prices by 16% and reduce the degree of expansion of crop area harvested, thereby reducing GHG emissions relative to the reference scenario.

Investments can make agriculture part of a 2°C climate trajectory

The assessment of technical mitigation options shows that much larger reductions in emissions can be achieved in agriculture. By 2030, these have a mean non-CO_2 mitigation potential equivalent to 715 million tons of CO_2 per year, and a mean CO_2 sequestration potential of 1,153 million tons per year. The mean cost of generating these levels of technical mitigation is USD 6.5 billion per year in 2030, rising to USD 8.5 billion annually by 2050. Together with the emissions savings generated by agricultural productivity growth, this technical mitigation helps the food system meet an emissions trajectory by 2030 that is consistent with 2°C of warming. The combination of technical mitigation expenditure and higher research expenditure does slow the expansion of land use driven by agriculture over this period. But they are not, in themselves, sufficient to achieve zero land use change induced by agriculture by 2050, which is critical if we are to achieve net zero, stabilizing global warming at below 2°C.

Investments can rein in water use and pollution

Additional investments and improvements in agricultural water resource technology and management for irrigated and rainfed areas would result in a 10% reduction in agricultural water use in 2030 compared to the reference scenario. These include accelerated investments in modernization of irrigation systems and water management for improved water use efficiency on irrigated cropland; water conservation in rainfed areas through the implementation of rainwater harvesting, broad-beds and furrows; and percolation dams and tanks and other technologies and management practices that improve plant water uptake capacity and soil water holding capacity. These investments would need to be targeted over large cropping areas and would require a combined increase in investment of USD 4.7 billion annually in the Global South. These increases are more than double (2.3 times) the annual investments in the reference scenario.

Increased investment in agricultural R&D would also improve fertilizer use efficiency, and, together with investment in technical options – precision agriculture techniques, integrated soil fertility management, conservation tillage, and improved management of the nutrient cycle for recycling and re-use in the livestock sector – would reduce non-point agricultural pollution from nitrogen in the Global South by 21% in 2030 and 35% in 2050, relative to the reference scenario. Phosphorous pollution from agriculture is projected to decline by 14% in 2030 and by 15% in 2050 compared to the reference scenario.

Now is the time to start closing the gap

To sum up the estimated investment gap, combining the agricultural R&D investments of USD 4 billion per year required to nearly end hunger by 2030, and the investments of USD 6.5 billion per year in technical climate smart options needed by 2030 to put the food system on an emissions trajectory consistent with 2°C of global warming (although not achieving zero land use change from agriculture), the innovation investment gap is USD 10.5 billion annually. Additional investments of USD 4.7 billion in innovation for water use efficiency and water conservation would make substantial progress toward the SDG6 water resource goals. Together these investments go a long way to meeting the targets, but they are not fully sufficient. Supporting policies and investments are required in such areas as value chains, finance, extension, gender-responsive policies and investments, social protection, water management and the implementation of carbon payments and smart subsidies.

1. Introduction

If the world is to achieve the Sustainable Development Goals (SDGs), succeed in stabilizing global warming at below 2°C, and adapt to the climate change this warming will bring, agricultural systems must transform significantly by 2030. It will not be easy. A rising global population, rapid income growth and urbanization are having profound effects on the demand and patterns of agricultural production (Godfray et al. 2010; Hawkes et al. 2017; Rosegrant et al. 2017). While hunger persists for too many people, diets continue to shift toward convenience foods and fast foods (Ruel et al. 2017; Fan et al. 2019). There is increased consumption of fruits and vegetables; growing demand for sugar, fats and oils; and rapid growth in meat consumption and therefore demand for feed grains or other livestock feeds (Thornton 2010; Godfray et al. 2010; Kearney 2010; Rosegrant et al. 2017). As these demands put pressure on food systems, sustainable food production growth also faces challenges from climate change, with higher temperatures and changing precipitation patterns as well as a likely increase in weather variability (Smith et al. 2018; Mbow et al. 2019).

At the same time, agriculture itself is a major contributor to greenhouse gas (GHG) emissions, so sustainable intensification needs to contribute to climate change solutions by reducing GHG emissions and sequestering carbon (Smith et al. 2018; Mbow et al. 2019). Agriculture needs to use less land if the world is to reverse deforestation and halt the global collapse in biodiversity. And it needs to use less water: amid rapidly growing demand (Damania et al. 2017), there must be a change in the wasteful irrigation management that unnecessarily depletes groundwater around the world and harms the quality of both agricultural and non-agricultural water supplies.

A transformation this large and rapid will require investment in innovations for sustainable agriculture intensification. These are innovations that seek to produce the food needed to meet changing human needs while simultaneously ensuring the long-term productive potential of natural resources, such as water and land resources, and the associated ecosystems and their functions. This report aims to show the size of that investment.

Specifically, this report aims to identify the innovation investment gap that needs to be filled to ensure that sustainable agriculture intensification supports the achievement of specific global goals:

- Ensuring that less than 5% of the world's population are at risk of hunger by 2030 (SDG2, using the FAO threshold for zero hunger) (FAO et al. 2015).
- Reducing and sequestering emissions in agriculture, and stopping emissions from land use change for food production, on a trajectory consistent with stabilizing climate below 2°C (SDG13 and the Paris Agreement).
- Supporting adaptation of the agricultural system to a changing climate (SDG13 and the Paris Agreement).
- Making substantial improvements in the efficiency of water use in agriculture (SDG6) and reductions in agricultural water pollution (SDG6).

2. Methodology

For this study, innovation for sustainable agriculture intensification is defined as the creation, development and implementation of new technologies, techniques and management practices for sustainable productivity growth, climate mitigation and water resource improvement that drive progress toward achieving the above goals and trajectories. The specific innovation investments that are analyzed are:

- Public and private investments in agricultural research and development (R&D).
- Investments to support adoption of innovative technologies for climate change mitigation in agriculture through carbon payments or other forms of targeted subsidies or payments of environmental services (technical mitigation options).
- Investment in innovative management and technology for water use efficiency (WUE) and soil water holding capacity (SWHC).

Analysis of the investment requirements and investment gap to 2030 used model-based investment scenarios combined with analysis of specific climate smart and resource-saving technical options as well as management practices that can reduce GHG emissions and increase GHG sequestration. SDG2 (zero hunger), SDG6 (clean water and sanitation), SDG13 (climate action) and the Paris Agreement on climate change provide the specific sustainability context in which the investment gaps are evaluated; the targets and indicators of progress used are detailed in Annex 1. The total investment gap includes the required investment in agricultural R&D and the required investment in climate smart and resource-saving technical options and management practices. In addition to showing the impacts of the gap-closing investments on hunger and GHG emissions – including CO_2 and non-CO_2 (methane and nitrous oxide) emissions – the analysis shows the impacts of these investments on water use and quality, per capita income, gross domestic product (GDP) and food prices. Results are reported both for 2030 and 2050 to show the longer-term impacts of gap-closing investments.

IMPACT global food model

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is an integrated modeling system that combines information from climate models (Earth System Models), crop simulation models (Decision Support System for Agrotechnology Transfer), and river basin level hydrological and water supply and demand models linked to a global, partial equilibrium, multimarket model focused on the agriculture sector. It is connected to a global general equilibrium model, GLOBE (see Robinson et al. 2015 for a detailed description of IMPACT). The link with the GLOBE model enables the assessment of the economy-wide impacts of climate change and agricultural investments, including GDP and per capita income, which are essential for determining the rate of return to investments. The output from IMPACT also provides the drivers for important post-IMPACT solutions analyses that generate the effects of alternative scenarios on the share and number of hungry people, GHG emissions and agricultural water pollution. The model offers a high level of disaggregation, with 159 countries, 154 water basins and 60 commodities. See Annex 1 for more on the model, our analysis and its limitations.

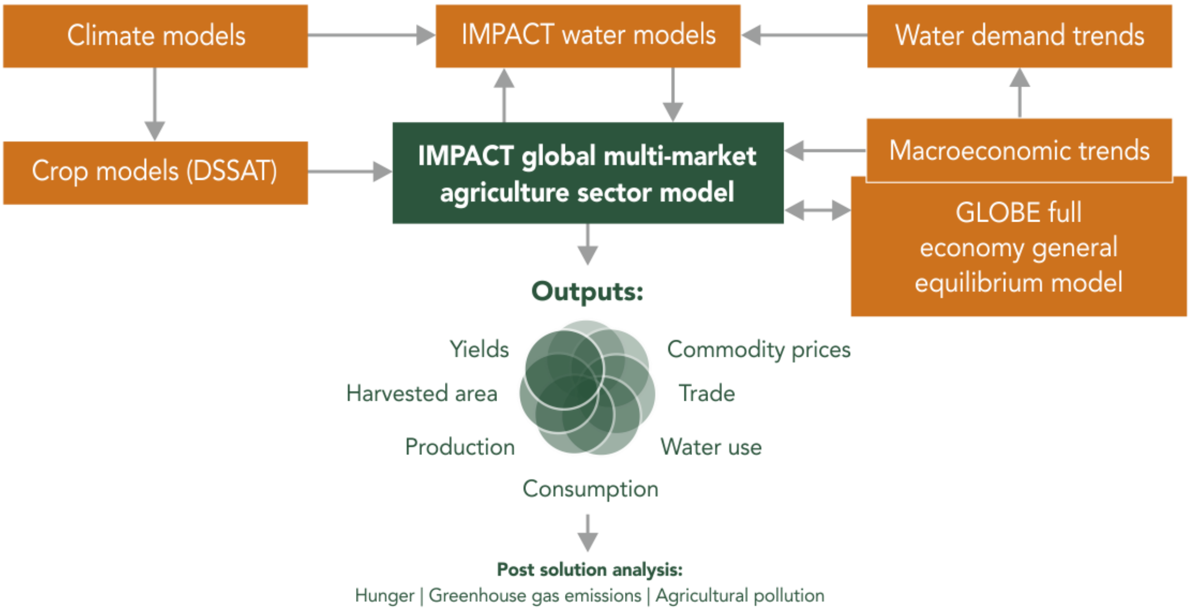

Figure 1. Structure of the IMPACT system of models.

Investment scenarios

Along with a reference business as usual scenario, two sets of alternative investment scenarios in IMPACT were analyzed for this report (Table 1):

1. Productivity enhancement through increased investments in agricultural R&D, including through the international public research institutions of CGIAR, national agricultural research systems (NARS) and private entities.
2. Improved water resource management.

Table 1. Summary of investment scenarios.

Scenario Grouping	Scenario	Scenario Description
Reference	**REF_HGEM**	Reference scenario with RCP 8.5 future climate using HadGEM global circulation model
Productivity enhancement	**HIGH**	High increase in R&D investment across the CGIAR portfolio
	HIGH+NARS	High increase in R&D investment across the CGIAR portfolio plus complementary NARS investments
	HIGH+NARS+REFF	High increase in R&D investment across the CGIAR portfolio plus complementary NARS investments plus increased research efficiency
	HIGH+NARS+REFF +PRIV	High increase in R&D investment across the CGIAR portfolio plus complementary NARS investments plus increased research efficiency plus increased private investments
Improved water resource management	**WUE**	Irrigation expansion plus increased water use efficiency
	SWHC	Investments to increase soil water holding capacity

For the reference scenario, **REF_HGEM**, investments in agricultural R&D by CGIAR are projected to average USD 1.7 billion per year between 2015 and 2050 in real 2005 dollars, while annual NARS investment in the Global South averages USD 6.4 billion per year (Annex 2, Table A2.1). The largest investments are projected in sub-Saharan Africa (SSA) (USD 2.2 billion per year) and Latin America and the Caribbean (LAC) (USD 1.8 billion per year). In most regions, the larger contribution to agricultural research will come from investments from NARS. The exception is SSA, where about half of the investments will come from CGIAR.

Four alternative scenarios seek to enhance agricultural productivity through increased investment in agricultural R&D. These four scenarios vary in level, source and efficiency of investment (Annex 2, Table A2.2). Each of these scenarios also uses SSP2 and RCP8.5, so that the results reflect changes in investment, not changes in underlying socioeconomic conditions and climate change. The **HIGH** R&D scenario incorporates yield gains from increasing investments in CGIAR R&D and was developed in collaboration with all 15 CGIAR centers through the Global Futures and Strategic Foresight program. As a starting point, each center quantified potential yield gains for their respective commodities (including crops, livestock and fish) in the Global South across SSA, LAC, South Asia (SAS), East Asia and the Pacific (EAP) and the Middle East and North Africa (MEN) with increased agricultural R&D investment. The **HIGH** scenario adds USD 2.1 billion annually to the reference costs for CGIAR investment in **REF_HGEM**, heavily concentrated in SSA.

In the scenario **HIGH+NARS** the increased investment by CGIAR is complemented by an increase in NARS spending in the Global South of USD 1 billion per year. The largest shares of this increase are in SSA and MEN, which contribute almost two thirds of additional NARS investments.

HIGH+NARS+REFF adds investments in higher research efficiency, with the result that the yield impact of investments is 30% higher and the maximum improvement is achieved by 2040, 5 years earlier than in the **HIGH** scenario. Research efficiency is gained through advancement in breeding techniques, including further advances in genomics and bioinformatics and high throughput gene sequencing, as well as more effective regulatory and intellectual property rights systems that reduce the lag times from discovery to deployment of new varieties. Investment in increased research efficiency adds another USD 0.42 billion per year to this scenario.

HIGH+NARS+REFF+PRIV, the most extensive R&D scenario, adds an increase in private sector investments of 30% to the higher CGIAR, NARS and research efficiency investments. This adds USD 0.52 billion per year in private investment, with nearly 40% spent in EAP and SAS. Combining all above R&D costs, the **HIGH+NARS+REFF+PRIV** investment scenario requires an additional USD 4 billion per year above the reference scenario, an increase of 41% compared to the reference scenario investments. The private sector accounts for 13% of the additional investments in this scenario.

In the reference scenario **REF_HGEM**, investments in improved water use across the Global South are projected at USD 2.2 billion per year. Most of these investments are projected in EAP and SAS, which account for almost 80% and 77% of irrigated area in the Global South in 2010 and 2050, respectively. Baseline investments in soil water management technologies are synthesized from previous studies and are estimated to be USD 1.3 billion per year for the Global South.

Two alternative water scenarios focus on investments and improvements in agricultural water resource technology and management that affect crops and livestock directly through changes in water availability, and livestock indirectly through changes in feed prices. They include accelerated investments in the modernization of irrigation systems and water management for improved water use efficiency on irrigated cropland (**WUE**). They also include water conservation in rainfed areas through the implementation of rainwater harvesting; broad-beds and furrows; and percolation dams, tanks and other technologies and management practices that improve plant water uptake capacity and soil water holding capacity (**SWHC**). The projected increases in innovation investment in **WUE** are USD 3.66 billion per year and in **SWHC** are USD 1.03 billion per year.

Technical mitigation options

The results from the R&D scenarios show that, in addition to meeting the SDG2 target of ending hunger, the gap-closing investments of **HIGH+NARS+REFF+PRIV** make important contributions toward SDG6 and SDG13. However, they do not achieve the CO_2 or non-CO_2 emission reduction targets for agriculture's contribution to a 2°C or 1.5°C climate trajectory. Therefore, additional investments are required to promote the adoption of climate smart and resource-conserving technical options that can achieve GHG emission reduction outcomes consistent with the Paris Agreement and SDG13, when combined with the reductions achieved through investment in agricultural R&D. The second part of the investment gap is therefore calculated as the additional investment required in technical mitigation options to achieve the targets for non-CO_2 and CO_2 emission reductions and sequestration in agriculture in 2030 that are consistent with 2°C and 1.5°C climate change trajectories.

The analysis of technical options draws on the available evidence in the literature regarding the potential impact of adopting climate smart techniques and management practices on GHG emissions, the cost of adoption for these practices, and the adoption potential of technical options. The four agricultural activities included in the analysis are cropland management, rice management, pasture management and livestock management, as defined in IPCC publications (Smith et al. 2007; IPCC 2014).

3. Results of investment scenarios by 2030

An additional USD 2.1 billion per year in international public R&D above the reference scenario counters the impact of climate change on hunger

All of the high investment scenarios meet the climate adaptation target, specified as the extent to which the gap-filling investments reduce hunger with climate change to no climate change levels. This target is assessed by comparing the investment scenarios, which include climate change under RCP 8.5, with a reference scenario without climate change. This no climate change scenario is identical to the **REF_HGEM** scenario, except that it models a climate scenario without climate change. Under the no climate change scenario, the global number of hungry people is 520 million in 2030 (Mason-D'Croz et al. 2019: Figure 9). This is considerably lower than the 586 million in the **REF_HGEM** scenario with climate change, showing the negative effect of climate change on progress in reducing hunger. However, all of the scenarios with higher investment in agricultural R&D – including **HIGH**, with its additional investment of only USD 2.1 billion in international public R&D – outperform the no climate change scenario, meeting the adaptation target and preventing 66 million people from being pushed into risk of hunger by climate change (Annex 2, Table A2.3).

USD 4 billion per year in R&D brings the population at risk of hunger below 5% in most regions – but not in SSA

As is shown below, the rise in productivity growth under the increased investment in agricultural R&D scenarios boosts per capita income and results in lower food prices, which in turn increases the demand for food, particularly for lower income groups. The result is that, for the Global South, the population at risk of hunger is reduced by 22% under the **HIGH+NARS+REFF+PRIV** scenario relative to the reference scenario in 2030, less than half its 2010 level (Annex 2, Table A2.3). The biggest reductions in hungry people to 2030 are in SAS. The **HIGH+NARS+REFF+PRIV** and **HIGH+NARS+REFF** scenarios achieve the SDG2.1 target at the 5% share of hunger in EAP, SAS and LAC – an impressive achievement in the short time remaining until 2030.

SSA remains well above the SDG2.1 target with an 11.8% share of hunger in 2030, although this is a major improvement relative to its 24.3% share of hunger in 2010. After 2030, the number of hungry in SSA falls sharply as the effects of agricultural productivity growth accumulate, and by 2050 the region reaches a share of 5.3% at risk of hunger. Given the lags from investment in R&D to impacts on productivity and hunger, it is not feasible to design an even higher R&D investment scenario to try to achieve the 5% target for SSA by 2030 while still improving performance elsewhere. Moreover, other types of investment and policies are needed to address persistent hunger, including income transfers and social safety nets.

In the improved water resource management scenarios, small changes in prices and income lead to insignificant changes in overall welfare. Nevertheless, improving water use efficiency has positive effects on overall food consumption, although at a much smaller scale than other alternative investment scenarios. While the increases in calorie availability are small, they still speed up the reduction of the population at risk of hunger across the Global South, with hunger reductions relative to the reference of 2% and 3% respectively for **WUE** and **SWHC** in 2050.

R&D investments bring down emissions by 402 $MtCO_2eq$ in 2030

The **HIGH+NARS+REFF+PRIV** scenario contributes non-CO_2 emission reductions of 291 $MtCO_2eq$ per year by 2030, relative to the reference scenario. This is due to lower nitrous oxide release from fertilizer use and reduced methane from rice and livestock production (Annex 2, Table A2.8). The scenario also achieves CO_2 emission reductions of 111 million tons (Mt) per year from the prevention of deforestation and grassland conversion due to innovations that enable sustainable agriculture intensification and thus slow the expansion of cropland.

Despite contributing to climate change mitigation, this scenario does not fulfill agriculture's contribution to a 2°C climate trajectory. Total global GHG emissions from all sources were 52,000 $MtCO_2eq$ in 2015 (Crippa et al. 2021). According to FAO (2021a), direct agricultural emissions were about 5,450 $MtCO_2eq$ in 2015. Smith et al. (2014) summarizes estimates of total direct agricultural emissions range from 4,300 to 5,300 $MtCO_2eq$ per year (Smith et al. 2014, Figure 11.4), with 95% confidence intervals spanning 3,900 to 7,000 $MtCO_2eq$ per year. According to the Food Security Chapter of the IPCC Climate Change Land Special Report (Mbow et al. 2019), about 21-37% of total greenhouse gas (GHG) emissions are attributable to the food system, including emissions from agriculture and land use, storage, transport, packaging, processing, retail and consumption. Crop and livestock activities within the farm gate account for 9-14% of total global GHG emissions (consistent with the FAOSTAT and IPCC estimates of direct agricultural emissions above). Agriculture is also responsible for 5-14% of total GHG emissions through its impact on land use and land use change, and 5-10% from supply chain activities (Mbow et al. 2019). As described in Annex 1, the focus of this report is on direct agricultural emissions and the impact of investments on land use change. Changes in GHG emissions from supply chain activities are not analyzed in this report.

As noted in the section on targets and indicators in Annex 1, Wollenberg et al. (2016) estimated that reducing non-CO_2 emissions from agriculture by 1,000 $MtCO_2eq$ per year by 2030 is consistent with a pathway to limit warming in 2100 to 2°C above pre-industrial levels. R&D investments in agricultural productivity growth achieve 29% of this targeted reduction. Rogelj et al. (2018) estimated targets for these CO_2 emissions that are consistent with the 1.5°C pathway based on the set of scenarios outlined by IPCC (2018). The first target is to sequester 100 $MtCO_2$ per year by 2030, and 2,300 $MtCO_2$ per year by 2050. These estimates are based on a low-overshoot scenario and are at the upper end of required reductions (Rogelj et al. 2018; McKinsey 2020). The land use change avoided by R&D investments achieves the 2030 level required for consistency with the 1.5°C pathway.

As an additional target, the EAT-Lancet report (Willett et al. 2019) estimated that a 2°C trajectory will necessitate eliminating all CO_2 emissions from land conversion for food production by 2050 – achieving zero land use change from agriculture. The investment scenario does not meet this target, although progress is made in reducing deforestation due to slower expansion in crop area compared to the reference scenario. In the reference scenario, deforestation due to agricultural production from 2015 to 2030 is projected to be 9 million hectares (Mha) per year, and 7.3 Mha per year from 2030-2050. The reduction in deforestation is due to agricultural R&D expenditures, which increase crop yields and thus reduce the rate of crop area expansion. Taken together, these two estimates give an overall projected rate of deforestation due to agricultural production of 8.15 Mha per year, which is consistent with available evidence. According to FAO (2020), the annual global rate of deforestation was 10 Mha per year from 2015 to 2020, and it is estimated that 80% of global deforestation, 8 Mha per year, is caused by agricultural activities (Kissinger et al. 2012). Under the **HIGH+NARS+REFF+PRIV** scenario, the projected average annual reduction in deforestation is 925,000 ha per year from 2015 to 2030 and 1 Mha per year from 2030 to 2050. Thus, under **HIGH+NARS+REFF+PRIV**, the projected annual average rate of deforestation between 2015 and 2030 is 8.1 Mha per year, and 6.3 Mha per year between 2030 and 2050.

Another USD 6.5 billion per year in technical options is needed to deliver a mitigation trajectory

For this analysis we assess the potential for GHG mitigation from the adoption of technical mitigation options at a carbon price of USD 70/tCO_2eq. At this price, the mean non-CO_2 technical mitigation economic potential in 2030 is 715 MtCO_2eq per year (Annex 2, Figure A2.3). Adding this to the 291 MtCO_2eq per year in savings achieved by R&D investment above produces a total of 1,010 MtCO_2eq per year – just meeting the 1,000 MtCO_2eq per year that is consistent with a 2°C climate trajectory.

Technical mitigation for CO_2 – that is, carbon sequestration in agriculture – has a mean economic potential of 1,153 MtCO_2eq per year in 2030, rising to 1,365 MtCO_2eq per year in 2050 (Annex 2, Figure A2.4). This is more than sufficient to sequester the 100 MtCO_2 per year in agriculture that is consistent with a 2°C trajectory. It does not, however, meet the much higher 2050 level of 2,300 MtCO_2 per year for this trajectory. The combined mitigation from technical options and avoided land use change add up to 1,613 MtCO_2 per year by 2050, providing more than two thirds of the needed carbon sequestration to meet the 1.5°C trajectory.

The mean estimate for the annual cost of this technical mitigation is USD 6.5 billion in 2030, rising to USD 8.5 billion in 2050 (Annex 2, Figure A2.6). By comparison, Frank et al. (2018) estimated a cost of adoption for technical options to deliver direct non-CO_2 emission savings of 800 MtCO_2eq per year in 2030, at a price of USD 100/tCO_2eq, or USD 12 billion per year. This estimate is consistent with the estimate in this report, given the cost of achieving the additional 85 MtCO_2eq per year at a carbon price between USD 70/tCO_2eq and USD 100/tCO_2eq.

USD 4.7 billion per year in water resource management reduces blue water demand

The two scenarios focusing on water resource management (**WUE** and **SWHC**), with combined additional investments of USD 4.7 billion yearly, are highly effective in reducing the demand for blue water for irrigation (Annex 2, Tables A2.10 and A2.11). In the **WUE** scenario, blue water usage is projected to decline by 9% globally in 2030 relative to the reference scenario. The largest improvements are in LAC (21%), SSA (14%) and EAP (12%). Investments in soil water holding capacity (**SWHC**) reduce irrigation water demand by 1% in 2030, and 2.6% in 2050, compared to the reference scenario. These reductions are achieved by making more effective use of rainwater (green water), as the use of green water increases under this scenario. Compared to the reference scenario, **SWHC** provides the biggest reductions in blue water use in EAP, with almost a 3% decline in blue water demand in 2030, and around 2% declines in SSA and LAC.

Regions that are already affected by water stress do benefit from investments in water management, and especially from increased efficiency in water use. Under **WUE**, demand for blue water is projected to decline by 12% in MEN compared to **REF_HGEM**, and by over 6% in SAS. These savings are particularly important when we consider that 43% of irrigated areas in MEN and 57% in SAS are already equipped for irrigation with groundwater (Siebert et al. 2010).

R&D investments and technical options substantially improve water quality

Agricultural activities contribute large amounts of nitrogen (N) and phosphorus (P) to water bodies around the world. Water pollution creates adverse impacts on humans, the environment and the economy. The impact of agricultural productivity growth on these pollutants is assessed using IFPRI's global water quality model (IGWQM), which is linked to the IMPACT projections (see Annex 2). In the base year of 2005 there was global nutrient loading of 55 Mt of N and 2.6 Mt of P. The Global South accounted for 79% of N loadings and 84% of P loadings. In the **REF_HGEM** reference scenario, global N loadings increase to 76.8 Mt in 2030 and 89.4 Mt in 2050, while P increases to 3.4 Mt in 2030 and 4.3 Mt in 2050. Growth in GDP, population, income, crop and livestock production, and fertilizer use drives these substantial increases in pollution.

We develop an alternative scenario incorporating the improvements in N use and P use efficiency due to productivity growth from the IMPACT model, under **HIGH+NARS+REFF+PRIV** with corresponding reductions in fertilizer usage, as well as improvements from adoption of technical mitigation options (as described in Annex 2, p. 58). Together these substantially cut pollution. This scenario results in N loadings of 60 Mt in 2030 and 58 Mt in 2050, thus achieving zero growth and eventually reductions in N water pollution in the Global South. Compared to the reference scenario, there is a 21% reduction in N loadings in 2030 and a 35% reduction in 2050. P loadings continue to increase from 2010, but at a much slower growth rate, increasing to 3.2 Mt in 2030 and 3.4 Mt in 2050. Relative to the reference scenario, there is a 14% reduction in P loadings in 2030 and 15% in 2050.

R&D and water investments generate USD 2 trillion per year in economic benefits to the Global South

The agricultural R&D investment scenarios generate large increases in per capita income and GDP relative to the reference scenario. Under **HIGH+NARS+REFF+PRIV**, per capita income in the Global South increases by about 2% in 2030, and nearly 6% in 2050, relative to the reference scenario (Annex 2, Table A2.4). The large increases in investment in SSA generate the highest proportional per capita income gains among the various regions: 8% in 2030 and 23.5% by 2050.

The strong increases in per capita income are also reflected in big gains in GDP. Under **HIGH+NARS+REFF+PRIV**, USD 1.7 trillion is added to economies of the Global South in 2030 compared to the reference scenario, increasing to USD 9.1 trillion by 2050 (Annex 2, Table A2.5). SSA gains USD 397 billion in 2030 and USD 3 trillion in 2050. The two water efficiency scenarios also have small positive impacts on per capita income. The **WUE** scenario boosts GDP in the Global South by USD 170 billion in 2030 and USD 387 billion in 2050 relative to the reference scenario. Under **SWHC**, GDP in the Global South increases by USD 127 billion in 2030 and USD 711 billion in 2050 relative to the reference scenario.

R&D and investments reduce food prices by 16%

In aggregate across all crop groups, the countries of the Global South increase their net imports from the developed world between 2010 and 2050 under the reference scenario. Net imports for cereals increases by about 18%, and imports of meat increase almost six-fold to over 20 million tons between 2010 and 2050. Imports of pulses and oilseeds each increase 3.6- to 4.6-fold. The Global South is also projected to shift from being an exporter to becoming an importer of fruits and vegetables and roots and tubers.

Across all the alternative investment scenarios, increases in yields and production drive a reduction in food prices in 2030 and 2050 relative to the reference scenario (Annex 2, Table A2.6). Productivity enhancement scenarios result in substantially lower prices for all commodities. The aggregate price for oil crops decreases on average only by about 20% compared to **REF_HGEM** in 2050, whereas the decrease is over 44% for roots and tubers, 33% for cereals and 36% for meat.

Increasing production through improved water resource management pushes down prices by about 3% relative to the reference scenario. The largest price declines under WUE are observed for crops that are heavily irrigated, such as rice, cotton and wheat. The **SWHC** scenario leads to larger price decreases, with an almost 9% decrease for millet and 4% for rice and wheat. Dryland crops like pulses also see larger benefits under **SWHC** where improved water holding capacity benefits not only irrigated crops but rainfed areas as well.

4. Supporting policies and investments

The above analysis estimates a combined innovation investment gap of USD 10.5 billion annually for agricultural R&D and technical mitigation options, plus additional investments of USD 4.7 billion in water resource management, to make significant progress in line with SDG2, SDG6, SDG13 and the Paris Agreement. The estimated investments go a long way to meeting these goals and trajectories but are not sufficient on their own. Improvements in supporting policies and investments for sustainable intensification would further their impact. Some of the most important supporting policies and investments are discussed in detail in Annex 3, addressing:

- Agricultural value chains
- Finance
- Extension
- Gender-responsive policies and investments
- Social protection
- Water management
- Carbon payments and smart subsidies
- Agroecological and landscape approaches.

5. Comparison with other studies

Numerous estimates have been made of the cost of achieving various development goals, such as ending hunger, although methods and targets are often specified differently. Estimates vary depending on the specific questions being asked (Fan et al. 2018); the objective of the study; sectors and investments covered; whether climate change is considered; the methods, models and assumptions used; geographical coverage and numerous other factors (Mason-D’Croz et al. 2019). Estimates are therefore not directly comparable, but they can provide useful context.

ZEF and FAO (2020) use a marginal cost curve approach to estimate the cost of ending hunger by 2030, finding that total additional annual investments between about USD 39 billion and 50 billion are required. Investments and policies considered include agricultural R&D, agricultural extension services, agricultural information systems, small-scale irrigation expansion in Africa, female literacy improvement, child nutrition programs, scaling up existing social protection programs, crop protection, integrated soil fertility management, the African Continental Free Trade Agreement, and fertilizer use efficiency.

FAO et al. (2015) focus on the investments needed to ensure that people have adequate income and resources to get the food they need. To achieve this by 2030 would cost an additional USD 265 billion per year for social protection and pro-poor investments and expenditures, both public and private, in agriculture and rural development. This study looks at the broadest set of investments, including additional public investment in social protection and targeted pro-poor investments in rural areas combined with public and private efforts to raise investment levels in productive sectors.

Laborde et al. (2016), using the MIRAGRODEP dynamic global model, estimate that hunger can be ended by 2030 with additional annual investments of USD 11 billion from 2015 to 2030. These new public expenditures would fund three categories of interventions: (1) social safety nets directly targeting consumers through cash transfers and food stamps; (2) farm support to expand production and increase farmers’ incomes; and (3) rural development that reduces inefficiencies along the value chain and enhances rural productivity.

In a subsequent study, Laborde et al. (2020) find that USD 33 billion annually is needed to end hunger, double the incomes of small-scale producers by 2030 and maintain agricultural GHG emissions below the commitments made in the Paris Agreement. The study includes investments in interventions related to social protection, institutions such as farmers’ organizations, and education through vocational training. It also includes interventions provided directly to farmers, including farm inputs, R&D, improved livestock feed and irrigation infrastructure. Other interventions considered in this study include interventions to reduce post-harvest losses , to improve returns from sales, and to support the mix of services provided by SMEs, such as cooperatives, traders and processors.

Baldos et al. (2020) examine the required R&D investment costs to adapt to climate change, based on climate-driven crop yield projections generated from extreme combinations of crop and global circulation models. They find that offsetting crop yield losses projected by climate and crop models from 2006 to 2050 would require increased R&D adaptation investments between 2020 and 2040 totaling between USD 187 billion and 1,384 billion (in 2005 USD PPP). R&D-led climate adaptation could therefore offer favorable economic returns and deliver gains in food security and environmental sustainability by mitigating food price increases and slowing cropland expansion.

Dalberg (2021, forthcoming) provides an analysis of investment in innovation in agriculture, but they do not link the investment to hunger and climate outcomes. They estimate that the annualized innovation spending on agriculture in the Global South from 2000 to 2019 was USD 50-70 billion in 2019 constant dollars. Classifies spending estimates by innovation area, Dalberg find that the areas with the largest shares of funding are public and private R&D funding with 20%; marketing extension and behavior change with 33%; institutional and infrastructure with 20%; and product development with 15%. Although they are not conceptually identical, the Dalberg estimate of USD 10-14 billion for R&D can be compared to the USD 9.8 billion of agricultural R&D investment in the reference scenario in this paper.

Finally, previous studies using IFPRI's IMPACT model analyzed a broader set of investments to assess the impact of boosting agricultural productivity on food security and the environment in the context of climate change. Rosegrant et al. (2017) found that increased global investments in agricultural research, resource management and infrastructure (irrigation and rural roads), with the aim of increasing agricultural productivity and nearly ending hunger by 2030, would cost an average of USD 52 billion annually from 2015 until 2030. This is much higher than the cost estimated in this paper due to the inclusion of infrastructure. A comparison between the two papers indicates that shifting additional spending to agricultural R&D may be more cost effective in addressing hunger than large increases in infrastructure investment relative to recent trends. Nevertheless, expenditures on infrastructure remain important, with substantial investments in irrigation infrastructure and rural roads built into the reference scenario.

Overall, previous studies of investment gaps to end hunger have higher estimates of the gaps. These higher costs are generally because previous studies target multiple goals and/or because they include investments in broader development initiatives, including infrastructure such as rural roads and irrigation, rural development programs and social protection programs. The comparative magnitude of these gap estimates with the estimate in this report indicates that investment in innovation may have especially high impacts on ending hunger while also improving the performance of climate change mitigation, and reducing agricultural water use while improving water quality. Careful targeting of interventions to the hunger goal can also reduce the cost relative to the impact. Laborde et al. (2016)'s study does have a relatively low-cost estimate for ending hunger by 2030, at USD 11 billion annually, which it arrives at by combining the targeting of consumers with cash transfers and food stamps with farm support to expand production and increase farmers' incomes. Nevertheless, broader investments in social protection, infrastructure and value chains, together with reforms in the areas of gender-responsive policies, agricultural extension, finance for small farmers and water management, remain essential for sustainable agriculture intensification and economic development. This is addressed in Annex 3.

Table 2. Summary of investment gap estimates to meet global goals from other studies.

Study	Goals	Estimate	Investments considered
ZEF and FAO (2020)	End hunger by 2030	USD 39-50 billion	R&D, extension, information systems, small-scale irrigation in Africa, female literacy, child nutrition, social protection, crop protection, integrated soil fertility management, African Continental Free Trade Agreement, fertilizer use efficiency
FAO et al. (2015)	Adequate income and resources for all to access food by 2030	USD 265 billion	Social protection, pro-poor rural investment, public and private investment in productive sectors
Laborde et al. (2016)	End hunger by 2030	USD 11 billion	Social safety nets, farm support to raise production and incomes, rural development to reduce inefficiencies along the value chain and enhance productivity
Laborde et al. (2020)	End hunger and double incomes of small-scale farmers by 2030 while maintaining emissions below Paris Agreement commitments	USD 33 billion	Social protection, farmers' institutions, vocational training, farm inputs, R&D, improved feed, irrigation infrastructure, reduction of post-harvest losses, support to small and medium-sized enterprises
Baldos et al. (2020)	Offset yield losses projected by climate and crop models to 2050	USD 187-1,384 billion	R&D for climate adaptation
Rosegrant et al. (2017)	Increase agricultural productivity and nearly end hunger by 2030	USD 52 billion	R&D, resource management, infrastructure (irrigation and rural roads)

6. Conclusion

Using the IMPACT global food model, this report has estimated the investment gap in research and innovation for sustainable agriculture intensification in the Global South. Agricultural R&D investments of USD 4 billion per year have the potential to nearly end hunger by 2030 in all regions other than SSA. Another USD 6.5 billion per year, invested in technical climate smart options, can achieve 2030 GHG emission reductions that are consistent with the Paris Agreement 2°C and 1.5°C pathways – although without halting agricultural land use change by 2050, which is also a necessity for these pathways. Therefore, the estimated innovation investment gap to end hunger and reduce emissions by 2030 is USD 10.5 billion annually. Other investments of USD 4.7 billion in innovations for water use efficiency and soil water management would make significant progress toward the water use efficiency and pollution targets of SDG6.

The USD 4 billion of additional yearly R&D investments incorporates international public R&D by CGIAR, national R&D by NARS, advances in research efficiency and private agricultural R&D, which together reduce the risk of hunger below the targeted 5% of the population in EAP, SAS and LAC – an impressive achievement in the short time remaining until 2030. SSA remains well above the target, with 11.8% at risk of hunger in 2030, although this is a major improvement relative to the 24.3% share who were hungry in 2010. The international public investments alone (totaling USD 2.1 billion) are sufficient to prevent climate change from pushing 66 million more people into risk of hunger by 2030.

The agricultural productivity growth generated, along with the adoption of technical mitigation options, achieves non-CO_2 GHG emissions savings of 1,010 $MtCO_2eq$ per year in 2030, a reduction in line with agriculture's contribution to a 2°C climate pathway. Technical options and avoided land use change also achieve ample CO_2 emissions reduction and sequestration, totaling 1,200 $MtCO_2eq$ per year in 2030 – far higher than the estimated 100 $MtCO_2eq$ per year needed to support a 2°C climate trajectory. These investments do not achieve zero land use change from agriculture by 2050, which is also required to stabilize the climate below 2°C, but do reduce the rate of deforestation by an average of 925,000 ha per year by 2030.

The additional investments and improvements in agricultural water resource technology and the management of irrigated and rainfed areas reduce agricultural water use by 10% in 2030 compared to the reference scenario, an impressive accomplishment during a time of expansion in irrigated area and production. Increased investment in agricultural R&D also improves fertilizer use efficiency, and, together with investment in technical options – precision agriculture techniques, integrated soil fertility management, conservation tillage and improved management of the nutrient cycle for recycling and re-use in the livestock sector – results in a reduction of non-point agricultural pollution from nitrogen in the Global South by 21% in 2030 and 35% in 2050 relative to the reference scenario. This would generate important health and environmental benefits.

Along with achieving global goals, the investment scenarios generate enormous economic returns. R&D investment alone adds USD 1.7 trillion to the GDP of the Global South in 2030, and USD 9.1 trillion in 2050. In these countries investment raises per capita income by 2% in 2030 and nearly 6% in 2050 relative to business as usual. A combination of R&D and water resource management investments reduces food commodity prices by 16% globally in 2030.

These results show that increased investment in innovation could have powerful impacts on key sustainable development and climate goals between now and 2030, with the potential to bring us within reach of ending hunger in many parts of the world, achieve globally significant reductions in greenhouse gas emissions and generate strong economic benefits for the Global South. Improvements in supporting policies and investments would further enhance the impact of the investments and improve the prospects for meeting global goals in 2030 and beyond. These enabling conditions are elaborated in Annex 3, including value chains, finance, extension, gender-responsive policies and investments, social protection, water management, implementation of carbon payments and smart subsidies, and agroecological and landscape approaches.

In addition to reforms and investments in these enabling conditions, the results suggest that more transformational policies and investments are needed to reverse deforestation and boost carbon sequestration and mitigation, especially beyond 2030. Greater targeting of agricultural R&D on the development of climate smart varieties and breeds, and on lower cost climate smart farming systems and practices, could change the relative prices, costs and benefits of different interventions. This, in turn, could substantially improve climate mitigation by making the adoption of climate smart technology cheaper. If the targeted funding is taken from the existing or projected investment portfolio, careful monitoring and assessment of the impact of such a reallocation is needed to determine if there is a trade-off with the food security target – for example, if newly developed climate smart technology reduces yields and farm profitability. Evaluation of alternative investment portfolios with prospective transformational technologies and policies would provide additional insights into the future of sustainable agriculture intensification.

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Annex 1. Model and analysis

The IMPACT model for investment scenario analysis

The primary tool for the scenario analysis was IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), an integrated modeling system that combines information from climate models (Earth System Models), crop simulation models (Decision Support System for Agrotechnology Transfer), and river basin level hydrological and water supply and demand models. This information is linked to a global, partial equilibrium, multimarket model focused on the agriculture sector. It is linked to a global general equilibrium model, GLOBE (see Robinson et al. (2015) for a detailed description of IMPACT, and Willenbockel et al. (2018) for the link between IMPACT and GLOBE). The link with the GLOBE model enables the assessment of the economy-wide impacts of climate change and agricultural investments, including gross domestic product (GDP) and per capita income. Linking IMPACT and GLOBE allows quantitative analyses of the impact of changes in investment in innovation in the agricultural sector on the rest of the economy, including the effects on household income and GDP. The feedback from GLOBE to IMPACT captures the endogenous effect of changes in income on food demand, food prices, and hunger.

The model offers a high level of disaggregation, with 158 countries, 154 water basins and 60 commodities. The output from IMPACT also provides the drivers for important post-IMPACT analyses that generate the effects of alternative scenarios on the share and number of hungry people, greenhouse gas (GHG) emissions and agricultural water pollution. Detailed assumptions on supply and demand elasticities, productivity growth rates and other core modeling parameters in IMPACT are available at the open access resource on GitHub (https://github.com/IFPRI/IMPACT) and documented in Robinson et al. (2015). Annex 4 provides the range of national-level values by region for key parameters.

Targets, trajectories and indicators for the analysis

***SDG2*.** End hunger by 2030 (part of SDG target 2.1). The target of ending hunger is defined as *the reduction of hunger to a 5% share of population by 2030.* This target is based on the FAO et al. (2015) Achieving Zero Hunger report, which adopted "a prudential threshold of five percent of the population" as indicating ending hunger. The methodology is based on the reduction in hunger due to increased calorie availability for consumption. This target, together with the mitigation in line with Paris Agreement climate trajectories described below, are the measures that determine the agricultural innovation investment gap. For the other targets we measure progress based on the indicators described below, where the investment target defined by meeting the investment gap is achieved. Progress is measured relative to the outcomes under the reference scenario.

SDG6. Within SDG6, two targets have some relevance to innovation investment for sustainable agriculture intensification. SDG target 6.3 is: "By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally."

This target is primarily aimed at the water, sanitation and health (WASH) sector. The WASH sector is not analyzed here. However, we measure the progress toward this target from closing the investment gap in terms of improved agricultural water quality as *the reduction in agricultural pollution due to nitrogen and phosphorus loading from agriculture by 2030*, relative to the reference scenario.

SDG target 6.4 is: "By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity." With respect to sustainable agriculture intensification, we measure progress on this target as *the reduction in agricultural water use in 2030* due to investments, relative to the reference scenario.

SDG13 and Paris Agreement. SDG13 and the Paris Agreement provide broad targets for mitigation and adaptation. The SDG13 sets forth targets for climate action focused primarily on adaptation: to strengthen resilience and adaptive capacity to climate-related disasters; integrate climate change measures into policy and planning; build knowledge and capacity to meet climate change; implement the UN Framework Convention on Climate Change; and promote mechanisms to raise capacity for planning and management. The Paris Agreement calls for "a long-term goal of keeping the increase in global average temperature to well below 2°C above pre-industrial levels; and to aim to limit the increase to 1.5°C, since this would significantly reduce risks and the impacts of climate change." Wollenberg et al. (2016), drawing upon the results of leading integrated assessment models, estimated a global requirement of reducing non-CO_2 GHG emissions from agriculture by 1,000 $MtCO_2e$ per year by 2030 to limit warming in 2100 to 2°C above pre-industrial levels. This target of was estimated based on the findings of leading integrated assessment models: Reisinger et al. (2013) estimated a requirement for non-CO_2 mitigation of 930 $MtCO_2e$ per year in 2030; van Vuuren et al. (2011) estimated 1,370 $MtCO_2e$ per year; and Wise et al. (2014) estimated 920 $MtCO_2e$ per year (all cited in Wollenberg et al. 2016). We adopt this target as the mitigation requirement for investment in sustainable agriculture intensification. Targets have also been estimated for CO_2 emissions that are consistent with the 1.5°C pathway based on the set of scenarios outlined by IPCC (2018). Analysis of these IPCC scenarios established the following CO_2 objectives for agriculture, forestry and land use change: first, to eliminate CO_2 emissions from land use change (e.g., deforestation and other land conversion) for food production by 2050, by achieving zero land use change from agriculture (Willett et al. 2019); and second, to sequester 100 $MtCO_2$ annually by 2030 and 2,300 $MtCO_2$ annually by 2050. This sequestration pathway is based on a low-overshoot scenario and is at the upper end of required reductions in CO_2 outlined in these scenarios (Rogelj et al. 2018; McKinsey 2020).

SDG13 and the Paris Agreement do not specify a quantitative target related to the contribution of sustainable agriculture intensification to climate change adaptation. Investments for agricultural climate change adaptation should reduce the adverse effects of climate change. To operationalize an indicator for the adaptation impacts of the innovation investments in sustainable agriculture intensification investments estimated here, we adopt a definition of the progress on adaptation as the *extent to which the gap filling investments reduce hunger with climate change to lower than no climate change levels in 2030*, holding all other macro changes, such as income and population growth, constant. This adaptation assessment is implemented by comparing the hunger outcomes of the investment scenarios with the hunger outcomes in a reference scenario with no climate change.

The IPCC scenarios are defined by two major components. First, Shared Socioeconomic Pathways (SSPs) are global pathways that represent alternative futures for economic and population growth (O’Neill et al. 2014; O’Neill et al. 2015). Population growth and GDP growth assumptions in the reference scenario are drawn from SSP2, which is a middle-of-the-road scenario that is based on historical trends, and changes in historical trends, in economic and demographic growth. The second component in the IPCC scenarios is the Representative Concentration Pathways (RCPs), which represent potential greenhouse gas emission levels in the atmosphere and the subsequent increase in solar energy that would be absorbed (radiative forcing). There are four RCPs, which are named according to the approximate level of radiative forcing in 2100, which ranges from 2.6 watts per square meter (W/m^2) to 8.5 W/m^2. RCP8.5, which is the strongest climate change scenario, is used as the climate change scenario in the reference scenario. Following establishment of the reference scenario, additional scenarios are run to assess the gap in public and private agricultural R&D investment, defined as the additional annual investments above the business as usual reference scenario required to end hunger by 2030. Increased agricultural R&D affects hunger by boosting crop and livestock yields, reducing food prices and increasing farm income and economy-wide GDP through multiplier effects on the non-agricultural sectors. The lower prices and higher incomes boost food consumption. In addition to showing the projected impacts on hunger, the modeling results provide estimates of the effect of the gap-closing investments on agricultural water use, GHG emissions from agriculture and deforestation.

Annex 2. Scenarios and detailed results

Investment scenarios for agricultural R&D and water resource management

Increased agricultural R&D affects hunger by boosting crop and livestock yields, reducing food prices and increasing farm income and economy-wide GDP through multiplier effects on the non-agricultural sectors, which boosts food consumption. Scenarios assess the impact of increased agricultural R&D as well as innovation-supporting investments for irrigation expansion, water use efficiency and rural infrastructure in the Global South. Irrigation and water use efficiency investments increase crop yields and reduce prices, thereby generating higher incomes.

The impact of overall agricultural R&D investments is captured in the model based on agricultural investments in terms of productivity gains and subsequent impacts on environmental and other outcomes. In this report we build on previous work on cost estimation, such as Nelson et al. (2010), using data on research costs (investments) collected by the Agricultural Science and Technology Indicators (ASTI) program, as well as literature on the economic and productivity returns to investments in agricultural research (e.g., Evenson and Gollin 2003; Alston et al. 2011; Nin-Pratt 2015; Nin-Pratt 2016). This literature establishes a quantitative relationship between changes in the stock of investment in agricultural R&D and changes in agricultural productivity. The baseline private sector investment in agricultural R&D is estimated based on Fuglie (2016) and Pardey et al. (2006).

Table A2.1. Average annual investments in the Global South in the reference scenario (REF_HGEM), 2015-2050 (billion 2005 USD).

Region	R&D				Water	
	CGIAR	NARS	PRIV	Total	WUE	SWHC
EAP	0.07	1.54	0.74	2.35	0.94	0.34
SAS	0.26	0.71	0.6	1.57	0.76	0.17
SSA	1.11	1.11	0.05	2.27	0.13	0.39
MEN	0.09	1.41	0.14	1.64	0.07	0.11
LAC	0.2	1.59	0.21	2	0.31	0.28
DVG	1.73	6.36	1.74	9.83	2.21	1.29

Notes: Figures are average annual investments over 2015-2050. R&D-Research and Development; WUE-Water Use Efficiency; SWHC-Investments in Soil Water Management. Regions are: EAP-East Asia and Pacific; SAS-South Asia; SSA-sub-Saharan Africa; MEN-Middle East and North Africa; LAC-Latin America and the Caribbean; DVG-Global South.

Table A2.2. Average annual additional investments in the Global South (relative to the reference scenario), 2015-2050 (billion 2005 USD).

Region	R&D					Water	
	HIGH	+NARS	+REFF	+PRIV	Combined	WUE	SWHC
EAP	0.02	0.11	0.06	0.22	0.41	1.75	0.15
SAS	0.15	0.11	0.13	0.18	0.57	0.96	0.21
SSA	1.74	0.33	0.10	0.02	2.19	0.16	0.27
MEN	0.04	0.30	0.06	0.04	0.44	0.22	0.21
LAC	0.12	0.14	0.07	0.06	0.39	0.58	0.20
DVG	2.08	0.99	0.42	0.52	4.01	3.66	1.03

Notes: Figures are average annual investments over 2015-2050. **HIGH**, **HIGH+NARS**, and **HIGH+NARS+RE** assume the same level of increased investment from CGIAR. Regions are: EAP-East Asia and Pacific; SAS-South Asia; SSA-sub-Saharan Africa; MEN-Middle East and North Africa; LAC-Latin America and the Caribbean; DVG-Global South.

Investments in research take time to bear fruit, as new ideas can take years to develop and spread. To capture these lags, the investment-yield estimation model is based on the perpetual inventory method, where research investments contribute to the stock of knowledge over time. Knowledge decays as older technologies become obsolete or irrelevant. Productivity grows if the stock of knowledge grows at a faster rate than the stock of knowledge decays. The lag structure in the perpetual inventory method used here follows a gamma distribution in which R&D investments reach peak impact ten years after initial investment and then decline over time to zero impact ten years after peak impact. With regionally differentiated research elasticities and decay rates, these imputed lag structures would vary by region according to existing R&D capacity and the potential trajectories for each region. This approach allows us not only to estimate the baseline costs in research implied under business as usual to 2050, but also to estimate additional investments needed to adapt to climate change and make progress toward selected SDGs.

Accounting for both public and private investments, the first component of the investment gap is computed as the difference in investments between the reference scenario and the level of investments required to end hunger (SDG2 calorie-based target) in 2030. Investments in the scenario analysis focus on agricultural R&D and water and soil management. In addition to food security impacts, the impact on CO_2 and non-CO_2 emissions and emissions due to long-term productivity growth in agriculture are projected based on the outcomes of the investment scenarios. In the IMPACT modeling system, investments in agricultural R&D for productivity growth also influence projected GHG emissions by reducing commodity prices, crop area harvested, animal numbers and fertilizer use due to improved nitrogen use efficiency (using less nitrogen per unit of output), and by changing cropping and livestock production patterns.

Improvements in agricultural productivity in the reference scenario are represented by exogenous growth rates for each commodity and country, based on historical trends as well as expert opinion about future changes. We have developed an R&D investment-yield model to assess the investment required to achieve projected growth in agricultural productivity.

Yield gains were first expressed as potential changes in absolute yield levels and then translated into differential yield growth rates used in the IMPACT modeling framework. The final endogenous yields and output growth generated by the investment scenarios are functions of interactions between these growth rates and projected changes in prices, demand and other factors. Projected percentage increases in crop and livestock yields in 2030 relative to the reference scenario (**REF_HGEM**) are shown in Figures A2.1 and A2.2. Agricultural productivity in sub-Saharan Africa has lagged significantly behind the rest of the world, but with the heavy concentration of investment in agricultural R&D in this region in the investment scenarios, both crop and livestock yield growth in sub-Saharan Africa are projected to grow faster than other regions. Livestock yields in South Asia will also grow more rapidly than the developing country average, from their currently relatively low levels.

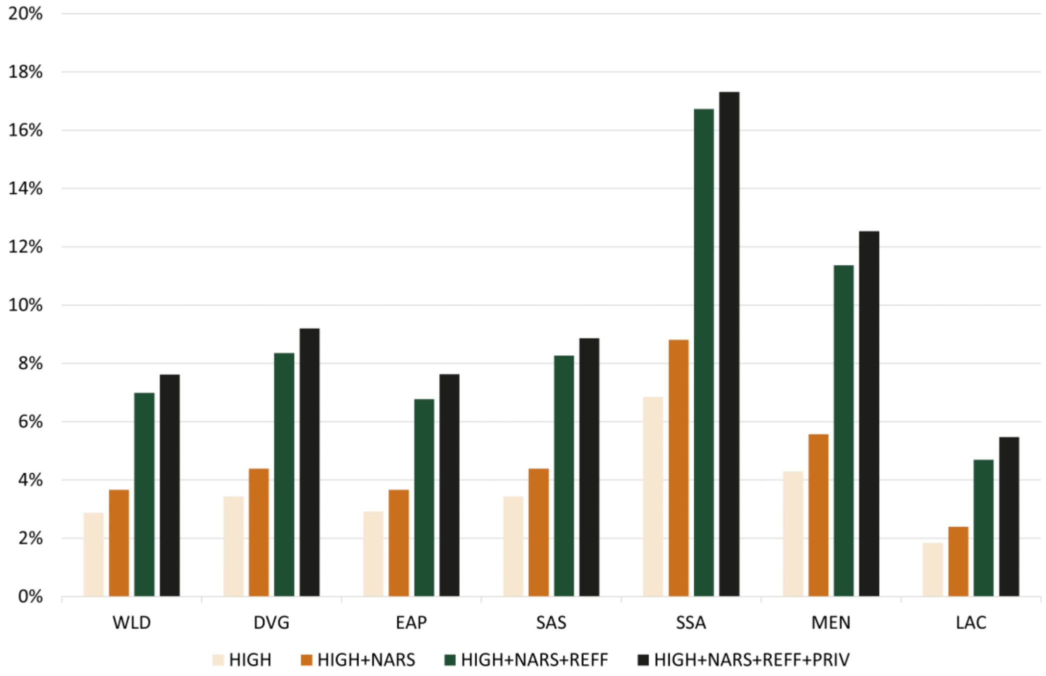

Figure A2.1. Projected changes in crop yields under alternative investment scenarios, percent difference from REF_HGEM in 2030, all crops.

Notes: WLD-World; DVG-Global South; EAP-East Asia and Pacific; SAS-South Asia; SSA-sub-Saharan Africa; MEN-Middle East and North Africa; LAC-Latin America and the Caribbean.

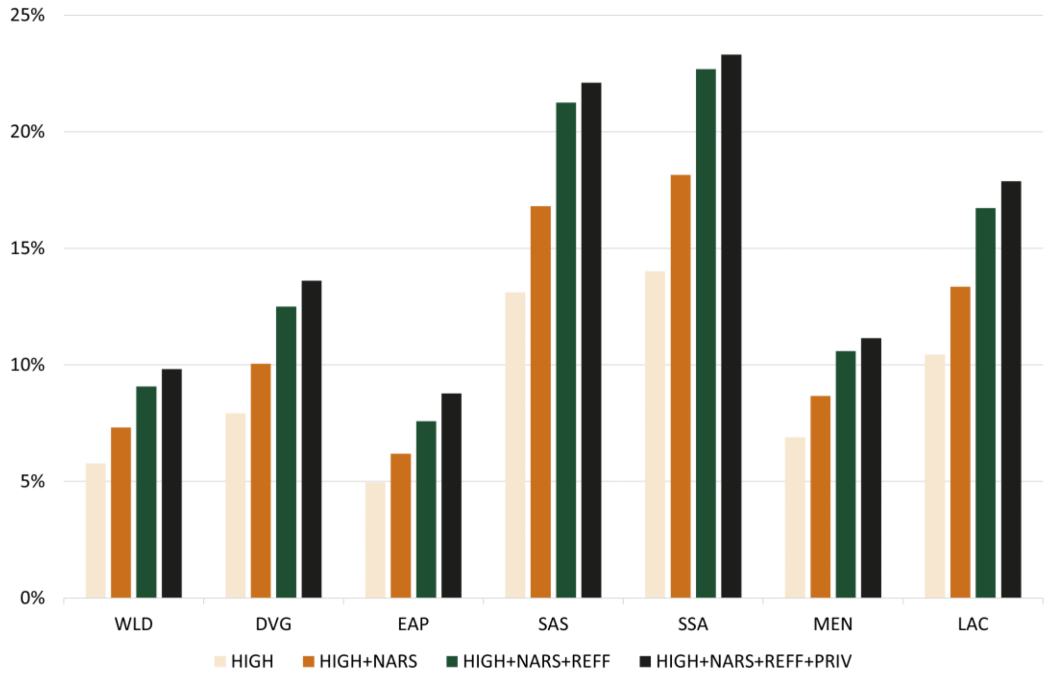

Figure A2.2. Projected changes in livestock yields under alternative investment scenarios, percent difference from REF_HGEM in 2030, all livestock.

Notes: WLD-World; DVG-Global South; EAP-East Asia and Pacific; SAS-South Asia; SSA-sub-Saharan Africa; MEN-Middle East and North Africa; LAC-Latin America and the Caribbean.

Hunger and economic outcomes

The share of people at risk of hunger is the percentage of the total population in a country that is at risk of suffering from undernourishment. This calculation is based on the empirical correlation between the share of undernourished within the total population and the relative availability of food and is adapted from the work done by Fischer et al. (2005) in the International Institute for Applied Systems Analysis (IIASA) World Food System used by IIASA and FAO. This approach is equivalent to FAO prevalence of undernourishment metric (FAO 2008). The number of hungry people is then computed as the share of people at risk of hunger times the population. The results for the impact of the investment scenarios are shown in Table A2.3 and are summarized in the main text above.

Sensitivity analysis run for another recent publication using IMPACT shows that the impact of investments in agricultural R&D on hunger have a robust effect across the range of potential climate and socioeconomic futures. Sulser et al. (2021) ran scenarios with combinations of socioeconomic assumptions for the Shared Socioeconomic Pathways SSP1, SSP2 and SSP3, and climate assumptions with Representative Concentration Pathways RCP4.5 and RCP8.5, using the Global Circulation Models HADGEM2-ES (Jones et al. 2011), IPSL-CM5A-LR (Dufresne et al. 2013), MIROC-ESM (Watanabe et al. 2011), NorESM1-M (Bentsen et al. 2013; Iversen et al. 2013) and GFDL-ESM2M (Dunne et al. 2012) for agricultural R&D investment scenarios similar to the **HIGH**, **HIGH+NARS**, AND **HIGH+NARS+REFF** scenarios in this paper. The results for these investment scenarios show a reduction in the population at risk of hunger in the developing world of 15% to 30% in 2030 and 2050, respectively, relative to the reference scenario. The more pessimistic combinations of socioeconomic and climate assumptions

(SSP3, RCP8.5 and HGEM) yield larger reductions in hunger as there is more room for improvement compared to the more optimistic scenario combinations. The results from this study are consistent with these results, with reductions in the population at risk of hunger in the developing world in 2030 of 15% to 28%, relative to the reference scenario, and of 20% to 31% in 2050 for the **HIGH**, **HIGH+NARS** and **HIGH+NARS+REFF** investment scenarios (Table A2.3).

Table A2.3. Prevalence of hunger in millions of people and as a share of the total population (percent).

			WLD	DVG	EAP	SAS	SSA	MEN	LAC
Population at Risk of Hunger	**2010**	REF_HGEM	838.1	823.3	271.3	268.5	209.5	29.3	39.5
	2030	REF_HGEM	601.8	586.2	120.2	166.2	226.8	35.8	35.8
		HIGH	515.1	500.3	111.7	130.7	189.8	33.3	33.2
		HIGH+NARS	496.1	481.6	109.9	122.5	182.2	32.8	32.6
		HIGH+NARS+REFF	433.3	419.4	103.9	96.0	156.0	31.1	30.7
		HIGH+NARS+REFF+PRIV	422.3	408.5	102.2	90.3	153.4	30.7	30.1
		WUE	584.6	569.2	118.1	157.0	222.4	35.2	35.1
		SWHC	589.0	573.4	118.8	161.8	220.6	35.5	35.4
	2050	REF_HGEM	491.6	475.9	108.8	99.8	199.5	38.2	28.8
		HIGH	393.9	380.7	94.0	85.4	141.8	33.4	24.8
		HIGH+NARS	376.6	364.0	91.9	83.4	130.9	32.6	24.0
		HIGH+NARS+REFF	341.4	329.1	87.6	80.1	106.0	31.3	22.6
		HIGH+NARS+REFF+PRIV	320.5	308.5	83.7	77.3	95.9	28.8	21.4
		WUE	482.5	467.1	107.4	97.4	195.5	37.7	28.3
		SWHC	473.4	458.0	106.8	97.4	187.3	37.5	28.0
Share at Risk of Hunger	**2010**	REF_HGEM	12.2	14.2	12.4	16.5	24.3	6.4	6.8
	2030	REF_HGEM	7.3	8.3	5.1	8.0	17.1	5.9	5.2
		HIGH	6.2	7.1	4.8	6.3	14.3	5.5	4.8
		HIGH+NARS	6.0	6.8	4.7	5.9	13.7	5.4	4.7
		HIGH+NARS+REFF	5.2	5.9	4.4	4.6	11.8	5.1	4.4
		HIGH+NARS+REFF+PRIV	5.1	5.8	4.4	4.4	11.6	5.1	4.4
		WUE	7.1	8.1	5.0	7.6	16.8	5.8	5.1
		SWHC	7.1	8.1	5.1	7.8	16.6	5.8	5.1
	2050	REF_HGEM	5.4	6.0	4.8	4.2	11.1	5.3	3.9
		HIGH	4.3	4.8	4.2	3.6	7.9	4.7	3.3
		HIGH+NARS	4.1	4.6	4.1	3.5	7.3	4.6	3.2
		HIGH+NARS+REFF	3.7	4.2	3.9	3.4	5.9	4.4	3.0
		HIGH+NARS+REFF+PRIV	3.5	3.9	3.7	3.3	5.3	4.0	2.9
		WUE	5.3	5.9	4.8	4.1	10.9	5.3	3.8
		SWHC	5.2	5.8	4.7	4.1	10.4	5.2	3.8

Notes: WLD-World; DVG-Global South; EAP-East Asia and Pacific; SAS-South Asia; SSA-sub-Saharan Africa; MEN-Middle East and North Africa; LAC-Latin America and the Caribbean.

Table A2.4. Average per capita incomes in the reference scenario (thousand 2005 USD per person) and percent differences under alternative investment scenarios in 2030 and 2050.

		WLD	DVG	EAP	SAS	SSA	MEN	LAC
2010	REF_HGEM	9.82	5.44	8.81	2.74	1.97	9.96	9.98
2030	REF_HGEM	17.23	12.42	22.33	6.86	3.73	17.04	16.88
	HIGH	0.50%	0.80%	0.50%	1.13%	3.59%	0.59%	0.20%
	HIGH+NARS	0.62%	1.00%	0.62%	1.41%	4.52%	0.75%	0.25%
	HIGH+NARS+REFF	1.09%	1.75%	1.10%	2.49%	7.77%	1.30%	0.45%
	HIGH+NARS+REFF+PRIV	1.21%	1.93%	1.28%	2.65%	8.04%	1.45%	0.53%
	WUE	0.12%	0.19%	0.15%	0.47%	0.11%	0.15%	0.02%
	SWHC	0.09%	0.14%	0.13%	0.09%	0.73%	0.05%	0.04%
2050	REF_HGEM	24.82	19.62	35.29	13.22	7.22	25.82	25.65
	HIGH	1.82%	2.63%	1.32%	3.05%	11.93%	1.67%	0.66%
	HIGH+NARS	2.27%	3.28%	1.64%	3.82%	14.94%	2.09%	0.83%
	HIGH+NARS+REFF	3.30%	4.76%	2.37%	5.62%	21.53%	3.03%	1.21%
	HIGH+NARS+REFF+PRIV	4.09%	5.91%	2.98%	7.71%	23.45%	4.07%	1.65%
	WUE	0.17%	0.25%	0.12%	0.64%	0.31%	0.20%	0.04%
	SWHC	0.32%	0.46%	0.33%	0.22%	2.44%	0.16%	0.13%

Notes: Projected value for REF_HGEM – all other scenarios show percent change from REF_HGEM. WLD-World; DVG-Global South; EAP-East Asia and Pacific; SAS-South Asia; SSA-sub-Saharan Africa; MEN-Middle East and North Africa; LAC-Latin America and the Caribbean.

Table A2.5. Regional increase in GDP under investment scenarios in 2030 and 2050 compared to REF_HGEM (trillion 2005 USD).

		WLD	DVG	EAP	SAS	SSA	MEN	LAC
2030	HIGH	0.709	0.700	0.262	0.161	0.177	0.061	0.024
	HIGH+NARS	0.885	0.873	0.325	0.200	0.223	0.077	0.030
	HIGH+NARS+REFF	1.558	1.534	0.576	0.353	0.384	0.134	0.053
	HIGH+NARS+REFF+PRIV	1.722	1.696	0.668	0.376	0.397	0.150	0.062
	WUE	0.172	0.170	0.078	0.066	0.006	0.016	0.002
	SWHC	0.128	0.127	0.067	0.013	0.036	0.005	0.005
2050	HIGH	4.149	4.067	1.056	0.957	1.545	0.308	0.126
	HIGH+NARS	5.181	5.077	1.305	1.199	1.935	0.387	0.157
	HIGH+NARS+REFF	7.524	7.365	1.890	1.763	2.789	0.560	0.229
	HIGH+NARS+REFF+PRIV	9.329	9.141	2.379	2.420	3.037	0.752	0.314
	WUE	0.395	0.387	0.095	0.200	0.040	0.037	0.008
	SWHC	0.723	0.711	0.266	0.068	0.316	0.030	0.025

Notes: WLD-World; DVG-Global South; EAP-East Asia and Pacific; SAS-South Asia; SSA-sub-Saharan Africa; MEN-Middle East and North Africa; LAC-Latin America and the Caribbean.

Table A2.6. Aggregated commodity prices, % difference relative to REF_HGEM in 2050.

		All	Cereals	Fruits and Vegetables	Meat	Oilseeds	Pulses	Roots and Tubers
2030	HIGH	-7%	-11%	-3%	-10%	-6%	-13%	-14%
	HIGH+NARS	-9%	-14%	-4%	-12%	-8%	-16%	-17%
	HIGH+NARS+REFF	-15%	-21%	-7%	-15%	-12%	-27%	-28%
	HIGH+NARS+REFF+PRIV	-16%	-23%	-9%	-16%	-13%	-27%	-28%
	WUE	-1%	-3%	-1%	0%	-1%	-1%	0%
	SWHC	-1%	-1%	-1%	0%	-1%	-2%	-2%
2050	HIGH	-14%	-22%	-6%	-20%	-13%	-25%	-25%
	HIGH+NARS	-17%	-25%	-8%	-24%	-15%	-30%	-31%
	HIGH+NARS+REFF	-23%	-32%	-10%	-27%	-20%	-41%	-42%
	HIGH+NARS+REFF+PRIV	-29%	-39%	-20%	-30%	-21%	-42%	-43%
	WUE	-1%	-2%	0%	0%	-1%	-1%	0%
	SWHC	-2%	-3%	-2%	0%	-2%	-3%	-3%

GHG emission reductions through productivity growth

Total global GHG emissions from all sources were 52,000 MtCO$_2$eq in 2015 (Crippa et al. 2021). Direct GHG emissions from agricultural production, together with related emissions from land use change and forestry, account for nearly one quarter of global GHG emissions (IPCC 2014). According to FAO (2021a), direct agricultural emissions were about 5,450 MtCO$_2$eq in 2015. IPCC (2013) estimates the total direct agricultural emissions to range from 4,300 to 5,300 MtCO$_2$eq per year, with 95% confidence intervals spanning 3,900 to 7,000 MtCO$_2$eq per year. According to the Food Security Chapter of the IPCC Climate Change Land Special Report (Mbow et al. 2019), about 21-37% of total GHG emissions are attributable to the food system, including emissions from agriculture and land use, storage, transport, packaging, processing, retail and consumption. (Crippa et al. (2021) provide a higher estimate of 34%, with a range of 25% to 42%). Crop and livestock activities within the farm gate account for 9-14% of total global GHG emissions, consistent with the FAOSTAT and IPCC estimates of direct agricultural emissions above (Mbow et al. 2019). Agriculture is also responsible for 5-14% of total GHG emissions through its impact on land use and land use change, and 5-10% from supply chain activities (Mbow et al. 2019). As described below, the focus of this report is on direct agricultural emissions and the impact of investments on land use change. Changes in GHG emissions from supply chain activities are not analyzed in this report. Although agricultural lands also generate large CO$_2$ fluxes both to and from the atmosphere via photosynthesis and respiration, this flux is nearly balanced on existing agriculture lands. Substantial carbon releases, however, result from the conversion of forested land, which is accounted for under the land use change category. According to Mbow et al. (2019), agricultural production is responsible for 5-14% of total GHG emissions through its impact on land use and land use change, including deforestation and peatland degradation.

The GHG emissions post-processor, combined with IMPACT results, give the GHG impacts generated by changes in crop and livestock production systems caused by agricultural productivity growth in the different scenarios. The empirical approach to estimate GHG emissions uses IPCC Tier 1 and 2 factors for GHG emissions. GHG emissions are estimated from three subcategories: synthetic fertilizers (nitrous oxide, N$_2$O), rice cultivation (methane, CH$_4$), and enteric fermentation (CH$_4$) in livestock. To simulate emissions, we employed the IPCC Tier 1 default factors for direct N_2O emissions arising from mineral N fertilizer application to managed soils. CO_2 equivalent (CO_2eq) for these emissions is computed by multiplying the amount of the GHG by its global warming potential.

Although a few efforts have been made to estimate N_2O emissions by using process-based simulation models, most have been limited to major cereal crops, such as maize, rice and wheat. To simulate emissions from all fertilizer use, we employed the IPCC Tier 1 default factors for direct N2O emissions arising from mineral N fertilizer application to managed soils (0.01 kg N_2O-N per kg N fertilizer applied) and to irrigated rice (0.003 kg N_2O-N per kg N fertilizer applied). These factors were multiplied by the N fertilizer consumption projected in IMPACT for each country and each crop/commodity. Note that the N_2O emissions we estimated exclude the indirect N_2O emissions from nitrogen leaching and runoff and from atmospheric nitrogen deposition.

To estimate CH_4 emissions from rice production, we combined crop/commodity yields projected by IMPACT with emission factors from Yan et al. (2009); hence, IPCC Tier 1 and Tier 2 methodologies are employed to estimate the global CH_4 emissions from rice fields. Emissions factors for this approach include the baseline emission factor for continuously flooded fields without organic amendments, a scaling factor for differences in the water regime during the cultivation period (e.g., single drainage and multiple drainage), and a scaling factor for both the type of organic amendment applied (e.g., rice straw and farmyard manure) and the amount. These CH_4 emissions from rice production were first calculated for a unit of area and then multiplied by rice production areas projected by IMPACT.

Livestock production is responsible for CH_4 emissions from enteric fermentation and both CH_4 and N_2O emissions from livestock manure management systems. Among several species of livestock, ruminants such as cows, buffaloes, camels and goats are important sources of CH_4 in many countries because their ruminant digestive systems have high CH_4 emission rates (IPCC 2006). Thus, CH_4 emissions from ruminants were estimated based on animal numbers projected in IMPACT (both slaughtered cattle and dairy animals) and emission numbers from the enteric fermentation section of FAOSTAT. To estimate emissions from the entire herd of ruminants, the projected numbers of each type of animal (slaughter cattle, dairy cows, goats, sheep, camels and buffaloes) were multiplied by the emission value obtained from FAOSTAT for per-head emissions from enteric fermentation.

Finally, the GHG emissions from changes in land cover driven by changes in crop area harvested and pastureland were computed. The relationship between changes in crop area and livestock production on the one hand and total cropland, pasture and forest area on the other hand were derived from simulations that linked IMPACT and LandSHIFT. LandSHIFT is a land use land cover change model (Schaldach et al. 2011). The estimated changes in land use driven by changes in area and livestock production were then combined with the Tier 1 GHG emissions coefficients for the relevant land use types to compute the estimated GHG emissions changes.

Table A2.7. Projected GHG emissions reductions and sequestration per year from agriculture due to investments in productivity growth, HIGH+NARS+REFF+PRIV, relative to the reference scenario.

Emissions Sources	$MtCO_2eq$ per year	
	2030	2050
Fertilizer (N_2O)	110	131
Rice (CH_4)	27	53
Livestock: (CH_4)	154	313
Total non-CO_2 GHG emissions reduction	291	497
Reductions in C emissions due to less land use change	111	248

Source: IMPACT modeling analysis.

Technical options for climate change mitigation

Restoration of agricultural soils is not included. Following IPCC guidelines for accounting for GHG emissions in agriculture (IPCC 2006), upstream and downstream emissions such as production of fertilizer and other inputs and value chain emissions are not included. The technical options considered are:

- Improved cropland management. This is an important potential method to reduce N_2O emissions and sequester CO_2. These can be achieved through agronomy (crop rotation and cover crops); conservation tillage and residue management; improved water management to reduce fertilizer runoff; and improved nutrient management through precision agriculture, advanced types of fertilizer, nitrogen use efficient new crop varieties and stabilized N sources (polymer-coated urea and nitrification inhibitors).
- Improved rice management for reduction of methane (CH_4). This includes midseason drainage of rice paddies and alternate wetting and drying.
- Pasture management, which can reduce GHG emissions through improved grasses and pasture management, improved manure management and use of legumes.
- Livestock management, which reduce CH_4 emissions with improved feeding practices and feed additives, improved manure management systems, and breeding and long-term management.

The assessment of technical options for GHG mitigation is based on data and research outcomes available from IPCC documents and other publications. Sources consulted include IPCC (2020, 2016, 2014), Beach et al. (2015), Herrero et al. (2016), Wollenberg et al. (2016), Smith et al. (2008, 2018), Frank et al. (2018), Smith et al. (2013), Del Grosso and Cavigelli (2012), Havlík et al. (2014) and EPA (2019). Key parameters considered in the assessment include the potential savings in tCO_2eq per hectare or per animal unit from adoption of technical options; the rate of adoption of technical options in terms of percentage of area or herd; and the cost of investment in mitigation from each technical option in USD per tCO_2eq. Investment costs include incremental annualized capital costs where applicable (many of the mitigation practices are more focused on changes in practices and inputs than capital expenditures) and estimated incremental changes in the annual costs of agricultural labor, fertilizer and other inputs. Following the practice in these sources, costs do not include revenue changes for farmers due to productivity increases or decreases related to the application of a technology (Frank et al. 2018). The assumptions regarding the range of values for the key parameters are shown in Table A2.8.

Table A2.8. Assumptions for analysis of technical climate mitigation potential and costs: range of values used.

(a) Cropland, rice and grassland/pasture management.

	Potential Adoption in 2030	Potential Adoption in 2050	Cost in 2030	Cost in 2050	CO_2 mitigation potential (biophysical)	CH_4 mitigation potential (biophysical)	NO_2 mitigation potential (biophysical)
	(% of crop area harvested)	*(% of crop area harvested)*	*(USD/tCO_2eq)*	*(USD/tCO_2eq)*	*(tCO_2eq per ha per yr)*	*(tCO_2eq per ha per yr)*	*(tCO_2eq per ha per yr)*
CROPLAND MANAGEMENT							
- Agronomy	50-70	45-100	10-15	11-18	0.40-0.58	n/a	0.04-0.085
- Tillage and residue management	50-80	45-100	9-15	10-18	0.24-0.40	n/a	0.02-0.06
- Nutrient management	50-80	45-100	8-15	9-18	0.20-0.30	n/a	0.07-0.12
- Water management	50-70	45-100	10-20	12-23	0.04-0.05	n/a	0.05-0.075
RICE MANAGEMENT	65-80	65-100	6-9	7-10	n/a	1.51-1.90	n/a
GRASSLAND/ PASTURE MANAGEMENT	20-40	20-40	7-10	8-12	0.40-0.46	0.01-0.04	n/a

(b) Livestock management.

	Cost in 2030	Cost in 2050	Livestock CH_4 (% mitigation potential)	Livestock CH_4 (% mitigation potential)
	(USD/tCO_2eq)	*(USD/tCO_2eq)*	*Global South*	*Global North*
LIVESTOCK SECTOR	8 - 12	9 - 13		
- Improved feeding practices, additives, etc.			5-10	10-12
- Manure management			2-4	4-5
- Breeding and long-term management			2-4	3-4

Note: n/a= not applicable. Sources: Estimated ranges of parameter values are drawn from IPCC (2016, 2014), Beach et al. (2015), Herrero et al. (2016), Wollenberg et al. (2016), Smith et al. (2008), Frank et al. (2018), Smith et al. (2013, 2018), Del Grosso and Cavigelli (2012), Havlík et al. (2014) and EPA (2019).

In agriculture, there is a relationship between the amount paid for GHG emission reductions (i.e. the price per tCO_2eq) and the level of mitigation realized. The economic potential for mitigation options in agriculture increases as the carbon price rises. For this analysis we assess the potential for GHG mitigation from adoption of technical mitigation options at a carbon price of USD 70/tCO_2eq. This carbon price was chosen for assessment based on review of the literature as a carbon price that would potentially generate GHG emissions reductions that would be consistent with the Paris Agreement pathways (see, for example, Frank et al. 2018; Beach et al. 2015; Del Grosso and Cavigelli 2012; Smith et al. 2014).

Based on these parameters we compute the potential mitigation in $MtCO_2eq$ per year in 2030 and 2050, and the annual cost of investment in mitigation in 2030 and 2050, in million USD per year. The key parameters vary across sources and ranges are reported in many of the sources. To capture this variability, calculations were made for a series of combinations of the parameters to assess a distribution of potential outcomes. These results allow us to compute the investment required to generate GHG emissions reductions consistent with the Paris Agreement pathways. The investment requirements represent the total carbon payments or payments for environmental services that need to be paid to induce the adoption of the technical options needed to generate mitigation consistent with a 2°C climate trajectory.

GHG emission reductions and sequestration through the adoption of technical options

Figures A2.3-A2.5 show the distribution of estimated potential mitigation of GHG emissions from technical options at a carbon price of USD 70/tCO_2eq. Figure A2.6 shows the investment required to generate this level of mitigation. In these box-and-whisker diagrams, the box shows the upper and lower quartiles of the distribution of the results, and the whiskers (the lines extending from the boxes) indicate variability outside the upper and lower quartiles (defined here as highest and lowest values within 1.5 times the interquartile range). Any dots outside the whiskers represent outliers. The means of the distribution are shown as dots within the boxes and the medians are shown as horizontal lines in the boxes.

As can be seen in Figure A2.3, the mean non-CO_2 technical mitigation economic potential in 2030 is 715 $MtCO_2eq$ per year, with a range of 606 $MtCO_2eq$ per year to 815 $MtCO_2eq$ per year; the mean potential in 2050 is 783 $MtCO_2eq$ per year, with a range of 647 $MtCO_2eq$ per year to 901 $MtCO_2eq$ per year. Comparisons with the literature are not precise because of the different methods employed for these estimations, but comparisons are nevertheless useful. Del Grosso and Cavigelli (2012) estimated that the potential for non-CO_2 agricultural mitigation from technical options at a carbon price of USD 50/tCO_2eq is 693 $MtCO_2eq$ per year in 2030; EPA (2019) estimates savings of 593 $MtCO_2eq$ per year in 2030 at "increasing prices"; Frank et al. (2018) estimate that adoption of technical options in 2030 can deliver direct non-CO_2 emission savings of 500 $MtCO_2eq$ per year at USD 40/tCO_2eq, and 800 $MtCO_2eq$ per year at USD 100/tCO_2eq in 2030; and about 850 MtCO2eq per year at USD 100/tCO_2eq in 2050. Thus, the estimates of economic potential made here are within the range found in the literature. The total cost (investment required in carbon payments) to generate this level of mitigation is shown in Figure A2.6. The mean cost of technical mitigation is USD 6.5 billion per year in 2030, with a range of USD 5.4-7.9 billion per year. We also ran a sensitivity analysis of the non-CO_2 technical mitigation economic potential with respect to carbon prices of USD 50/tCO_2eq and USD 100/tCO_2eq. Although the total cost of mitigation at USD 50/tCO_2eq is of course lower than for USD 70/tCO_2eq, at USD 3.1 billion per year, the mean potential savings is only 483 $MtCO_2$eq per year in 2030, far below the non-CO_2 agricultural mitigation that is needed to be consistent with the 2°C climate change pathway. At USD 100/tCO_2eq the mean potential non-CO_2 technical mitigation economic potential in 2030 is 887 $MtCO_2$eq per year, at a cost of USD 11.6 billion.

Direct comparators for global CO_2 sequestration potential at specific carbon prices are not available, but comparators for combined CO_2 and non-CO_2 mitigation potential are discussed below.

Combined total technical mitigation potential includes the values for non-CO_2 GHG and CO_2 emissions (Figure A2.5). The total CO_2 technical mitigation potential has a mean of 1,868 $MtCO_2$eq per year in 2030, with a range of 1,683-2,073 $MtCO_2$eq per year; and the mean potential in 2050 is 2,148 $MtCO_2$eq per year, with a range of 1,712-2,626 $MtCO_2$eq per year. In 2030, cropland management accounts for 49% of the total CO_2 emission reduction potential, rice management 10%, grasslands 22% and livestock 19%. The 2030 values fall between the Smith et al. (2014) estimates of mitigation potential in 2030 for the four categories of technical options analyzed here (cropland management, rice management, pasture management and livestock management) of approximately 1,575 $MtCO_2$eq per year at USD 50/tCO_2eq, and 1,950 $MtCO_2$eq per year at USD 100/tCO_2eq (estimated from Smith et al. 2014: Figure 11.13).

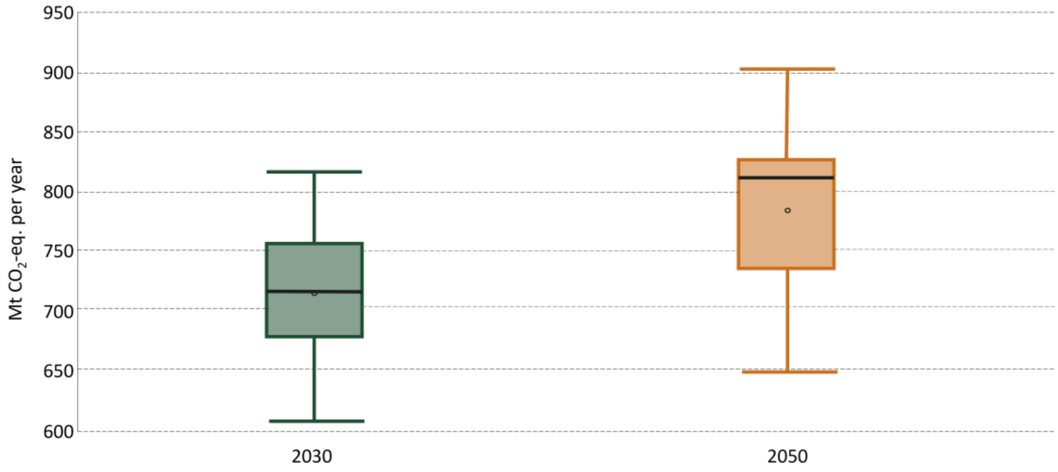

Figure A2.3. Agriculture sector non-CO_2 technical mitigation potential, 2030 and 2050, at a carbon price of USD 70/tCO_2eq.

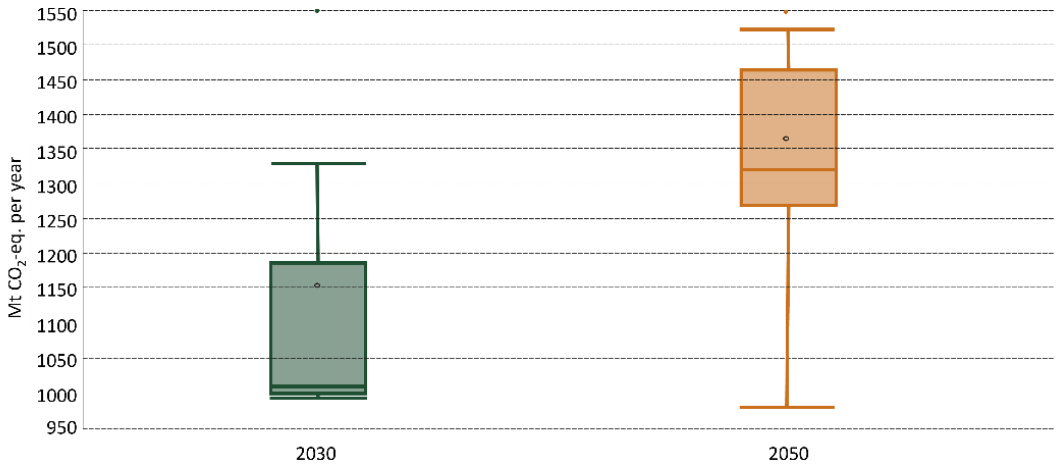

Figure A2.4. Agriculture sector CO_2 technical mitigation potential, 2030 and 2050, at a carbon price of USD 70/tCO_2eq.

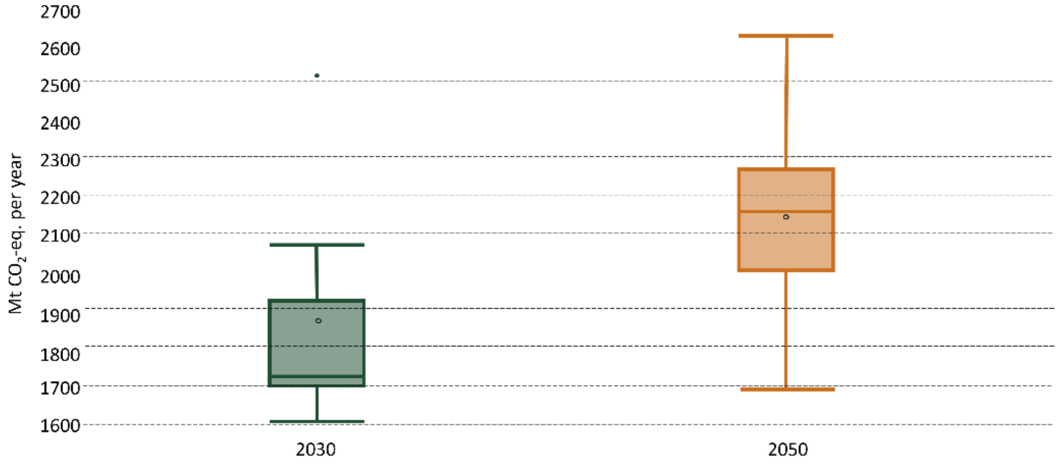

Figure A2.5. Agriculture sector total CO_2 technical mitigation potential, 2030 and 2050, at a carbon price of USD 70/tCO_2e.

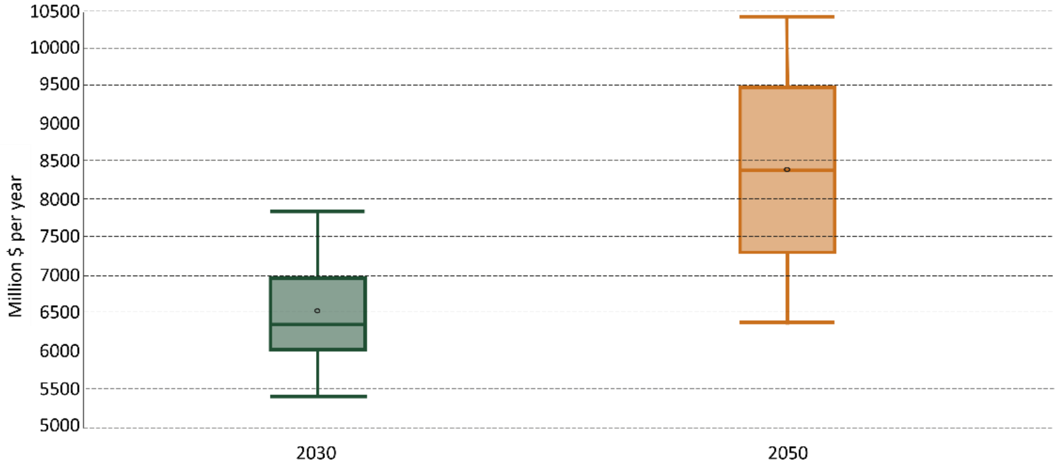

Figure A2.6. Cost of technical mitigation, 2030 and 2050, million USD per year, at a carbon price of USD 70/tCO_2eq.

The mean results for total CO_2 GHG emissions reductions from Figure A2.3 are further broken down by technical option in Table A2.9. The results show that the projected economic mean potential non-CO_2 GHG emissions reductions from technical options in agriculture are 1,868 $MtCO_2eq$ per year in 2030 and 2,148 $MtCO_2eq$ per year in 2050. In 2030, cropland management accounts for 49% of the total CO_2 emission reduction potential, rice management 10%, grasslands 22% and livestock 19%.

Table A2.9. Summary of mean potential total emissions reductions from technical options in agriculture at a carbon price of USD 70/tCO_2eq.

Technical mitigation options	$MtCO_2eq$ per year	
	2030	2050
CROPLAND MANAGEMENT	919	1152
-Agronomy	410	514
-Tillage and residue management	265	327
-Nutrient management	221	281
-Water management	23	30
RICE MANAGEMENT	187	209
GRASSLAND/PASTURE MANAGEMENT	402	422
LIVESTOCK	360	365
Total CO_2 mitigation potential	1868	2148

Source: Estimation by authors.

Water resources modeling and scenario costs

Water availability, including rainfall, streamflows and evaporation, is determined in a hydrological model that downscales precipitation and temperature from climate scenarios generated by the global circulation model. Water supply and demand by sector is determined in a water simulation model that allocates water across irrigation, livestock, domestic use and industrial use. Water supply and demand are solved in 154 river basins globally and are linked annually to the IMPACT economic model (Robinson et al. 2015). Two of the key drivers in this model are assumptions of trends in irrigation expansion and water use efficiency (WUE). As with assumptions of agricultural productivity, the reference assumptions used for these drivers are based on historical trends combined with expert opinion about future pathways. Total harvested area expands by about 18% in the projection period from 2010 to 2050.

The **WUE** scenario postulates improvement in river basin water use efficiency through modernization of irrigation systems together with water management reforms. FAO has defined modernization as “a process of technical and managerial upgrading of irrigation schemes combined with institutional reforms, if required, with the objective to improve resource utilization and water delivery service to farms” (Renault 1999). Modernization is the introduction of modern technologies, such as water application and distribution through pipes rather than open channels, and the use of remote sensing and computerized soil water sensors to trigger water applications. However, it also comprises older capital-intensive techniques, such as canal lining and land leveling. Investment in this capital-intensive hardware is outside the scope of innovation investment. Based on work by FAO and International Water Management Institute (IWMI) (Palanisami 1997; Inocencio et al. 2007; FAO 2016), per-hectare investment cost for modernization of irrigation systems is USD 2,144 for East, South, Southeast and Central Asia; USD 4,311 for sub-Saharan Africa and Latin America; and USD 953 for the Middle East and North Africa. These estimates are likely too high for the more recent, less capital-intensive modernization investments, but there is not adequate recent data to update the estimates. It is assumed that modernization is phased in over time, reaching 80% of irrigation systems by 2050.

For the **SWHC** scenario, many technologies and management strategies for soil water conservation are available. Soil and water conservation options for increasing plant water uptake capacity include bunds, ridges, broad-beds and furrows, micro basins, runoff strips, terracing and contour cultivation. Water harvesting options include surface micro dams, subsurface tanks, farm ponds, percolation dams and tanks, diversion, and recharging structures. Evaporation management includes dry planting, mulching, conservation agriculture and vegetative bunds (Cervigni and Morris 2016). These technologies have a wide range of costs and data is relatively sparse. Costs estimates range from USD 44/ha to USD 212/ha, depending on the type and location of interventions (Cervigni and Morris 2016; IWMI 2012; McCarthy 2011). For this analysis, we assume that a range of these interventions is phased in to 70% of rainfed area by 2050, with an average mean of USD 109/ha. The required innovation investments are the smart subsidies or payment for environmental services required to incentivize adoption, estimated at 30% of the total cost, drawing upon Cervigni and Morris (2016).

IMPACT uses the concept of basin efficiency, which is defined as the ratio of beneficial water depletion (crop evapotranspiration and salt leaching) to total irrigation water depletion at the basin scale, taking account of return flows from irrigation within the river basin. In the **WUE** scenario, basin efficiency in future years is projected to increase at a prescribed rate depending on investment in water management. For the **WUE** scenario, basin efficiencies improvements are phased in to increase by 15 percentage points. The **SWHC** scenario simulates the benefits of technologies, such as water harvesting, that increase the water holding capacity of soil or otherwise make precipitation more readily available to plants (i.e., effective precipitation). Improvements vary by region due to the different levels at which these kinds of technologies are currently being applied, with a maximum increase in effective precipitation of 5-15% by 2045.

Table A2.10. Global water use under alternative scenarios, billion cubic meters, projected to 2030 and 2050.

		BCM			% diff from REF_HGEM	
		2010	2030	2050	2030	2050
Bluewater	REF_HGEM	1,731	1,890	2,063	0.00	0.00
	HIGH	1,731	1,887	2,056	-0.11	-0.32
	HIGH+NARS	1,731	1,887	2,054	-0.14	-0.40
	HIGH+NARS+REFF	1,731	1,885	2,051	-0.24	-0.54
	HIGH+NARS+REFF+PRIV	1,731	1,884	2,044	-0.30	-0.91
	WUE	1,731	1,722	1,871	-8.86	-9.30
	SWHC	1,731	1,865	2,010	-1.30	-2.56
Greenwater	REF_HGEM	4,440	4,982	5,440	0.00	0.00
	HIGH	4,440	4,961	5,384	-0.43	-1.04
	HIGH+NARS	4,440	4,956	5,373	-0.53	-1.23
	HIGH+NARS+REFF	4,440	4,940	5,355	-0.85	-1.56

		BCM			% diff from REF_HGEM	
		2010	2030	2050	2030	2050
Greenwater	HIGH+NARS+REFF+PRIV	4,440	4,932	5,317	-0.99	-2.26
	WUE	4,440	4,971	5,427	-0.23	-0.23
	SWHC	4,440	5,103	5,692	2.43	4.64
Total	REF_HGEM	6,171	6,872	7,503	0.00	0.00
	HIGH	6,171	6,848	7,440	-0.34	-0.84
	HIGH+NARS	6,171	6,843	7,427	-0.42	-1.01
	HIGH+NARS+REFF	6,171	6,825	7,407	-0.68	-1.28
	HIGH+NARS+REFF+PRIV	6,171	6,816	7,361	-0.80	-1.89
	WUE	6,171	6,693	7,298	-2.60	-2.73
	SWHC	6,171	6,968	7,702	1.40	2.66

Table A2.11. Regional water use under alternative scenarios, billion cubic meters, projected to 2030 and 2050.

	Scenario		BCM			% diff from REF_HGEM	
			2010	2030	2050	2030	2050
EAP	Bluewater	WUE	416	379	383	-10.46	-12.09
		SWHC	416	411	412	-2.93	-5.52
	Greenwater	WUE	1252	1358	1443	-0.18	-0.18
		SWHC	1252	1388	1499	2.01	3.70
	Total	WUE	1668	1737	1826	-2.62	-2.94
		SWHC	1668	1799	1911	0.84	1.56
SAS	Bluewater	WUE	659	663	711	-6.64	-6.30
		SWHC	659	704	747	-0.89	-1.47
	Greenwater	WUE	847	927	985	-0.39	-0.30
		SWHC	847	954	1030	2.52	4.18
	Total	WUE	1506	1590	1696	-3.10	-2.91
		SWHC	1506	1658	1777	1.04	1.73
SSA	Bluewater	WUE	71	88	125	-11.93	-14.14
		SWHC	71	97	139	-2.32	-4.93
	Greenwater	WUE	697	859	1024	-0.13	-0.15
		SWHC	697	909	1138	5.67	11.05
	Total	WUE	768	947	1149	-1.36	-1.89
		SWHC	768	1007	1277	4.84	9.06
MENA	Bluewater	WUE	221	213	230	-12.14	-11.01
		SWHC	221	242	258	-0.14	-0.25
	Greenwater	WUE	86	90	91	-0.27	-0.38
		SWHC	86	93	97	3.19	6.18
	Total	WUE	306	303	321	-8.91	-8.23
		SWHC	306	335	355	0.76	1.43
LAC	Bluewater	WUE	137	132	152	-20.08	-21.23
		SWHC	137	162	184	-1.88	-4.51
	Greenwater	WUE	764	940	1111	-0.24	-0.28
		SWHC	764	960	1153	1.90	3.56
	Total	WUE	901	1072	1262	-3.19	-3.37
		SWHC	901	1122	1337	1.34	2.37

Agricultural water pollution

Agricultural activities contribute large amounts of nitrogen (N) and phosphorus (P), which make their way into water bodies. High risks from water pollution mean that adverse impacts on humans, the environment and the economy are likely to occur. We assess the impact of agriculture on these pollutants using IFPRI's global water quality model (IGWQM) linked to IMPACT agricultural projections. Global agricultural non-point source N and P loadings are estimated for the base year on a half-degree latitude-longitude grid, accounting for both crop production and livestock production systems. Projected loadings for crops are a function of growth in fertilizer use and rates of change in fertilizer use efficiency. The total quantities of livestock excreta and the quantities of excreta recycled to cropland as manure, and resultant N and P loadings, are simulated according to projected livestock animal population size in 2050, recycling rate, and efficiency of management of livestock waste.

Alternative investments in agricultural R&D influence the outcomes for N and P loadings through their impact on cropped area, fertilizer use and livestock production, and these outcomes are assessed in the scenarios. However, bigger improvements in N and P use efficiency may be possible through increased investment in breeding for enhanced nutrient use efficiency; adoption of sustainable agricultural methods such as nutrient efficient crop varieties and fertilizers formulated for more efficient nutrient uptake; adoption of advanced irrigation technology and improved water management; conservation tillage; and improved management of the nutrient cycle for recycling and re-use in the livestock sector.

In this model, global agricultural non-point source N and P loadings were estimated for the base year on a half-degree latitude-longitude grid, accounting for both crop production and livestock production systems. Projected loadings for crops are a function of growth in fertilizer use and rates of change in fertilizer use efficiency. The total quantities of livestock excreta and the quantities of excreta recycled to cropland as manure and resultant N and P loadings are simulated according to projected livestock animal population size in 2050, recycling rate, and efficiency of management of livestock waste (Xie and Ringler 2017; IFPRI and Veolia 2015).

Agricultural non-point loadings in the Global South in the base year of 2005 were 55 Mt for N and 2.6 Mt for P. Of this, 44 Mt of N and 1.8 Mt of P were from crops, and 12 Mt of N and 0.8 Mt of P were from livestock (Rosegrant et al. 2017). The Global South accounted for 79% of global N loadings and 84% of P loadings in the base year. East Asia and Pacific accounted for one third of global N loadings and South Asia one quarter. The share of the Global South in N loadings increases to 82% in 2030, while the share of P loadings stays nearly constant. In the **REF_HGEM** reference scenario, global N loadings increase to 76.8 Mt in 2030 and 89.4 Mt in 2050, and P increases to 3.4 Mt in 2030 and 4.3 Mt in 2050. Growth in GDP, population, income, crop and livestock production and fertilizer use drives these substantial increases in pollution.

We develop an alternative scenario, incorporating the improvements in N use and P use efficiency due to productivity growth, using the IMPACT model and improvements from adoption of technical options. Alternative investments in agricultural R&D for productivity growth influence the outcomes for N and P loadings through their impact on cropped area, fertilizer use and livestock production, and these outcomes are assessed using the **HIGH+NARS+REFF+PRIV** scenario. The estimated improvements are a 12% improvement in N use efficiency in 2030, and a 15% improvement in 2050, compared to the reference scenario; and a 7% increase in P use efficiency in 2030, and an 8% increase in 2050, generated by the investments in agricultural R&D for productivity growth under the **HIGH+NARS+REFF+PRIV** scenario. The estimated improvements also include a 10% improvement in N use efficiency in 2030, and a 24% improvement in 2050; and a 6% improvement in P use efficiency in 2030, and a 10% improvement in 2050, due to adoption of technical options. In addition, and analogously to the case of GHG emissions reductions through the adoption of technical options, improvements in N and P use efficiency are possible through the adoption of specific technologies. The estimated rates of improvement in N use efficiency are based on crop modeling of the estimated potential impacts on nitrogen losses through precision agriculture techniques, integrated soil fertility management and conservation tillage taken from Rosegrant et al. (2014). As these technologies are a subset of the GHG emission-reducing technologies discussed in the previous section, the cost of these technical options is accounted for in the cost of the technical options for mitigation. In the absence of direct modeling of potential improvements in P loading due to adoption of improved practices, the percentage efficiency improvements in P due to improve practices are estimated as proportional to the relative gains in N and P loading from the productivity investment scenario.

The combination of agricultural productivity-driven reductions in fertilizer usage, together with reductions from technical options, achieves substantial cuts in pollution. The improvements in pollution control under this scenario result in projected N loadings of 60 Mt in 2030 and 58 Mt in 2050, thus reversing increases in the initial years and achieving zero growth and finally reductions in N water pollution in the Global South by 2050 compared to the base year N loadings. Compared to the reference scenario, there is a reduction of 21% in N loadings in 2030 and 35% in 2050. P loadings continue to increase from the base year, but at a much slower growth rate, increasing to 3.2 Mt in 2030 and 3.4 Mt in 2050. Relative to the reference scenario, there is a reduction of 14% in P loadings in 2030 and 15% in 2050.

Limitations of the model and analysis

Common with the studies cited above, the analysis here relies on many assumptions and estimated agricultural and economic relationships. As a global economic model, IMPACT relies primarily on aggregate national statistics, together with sub-national down-scaling of climate and water resources, and must therefore represent detailed economic behavior in a stylized way (Mason-D’Croz et al. 2019). The coupling of a highly disaggregated agricultural partial equilibrium model like IMPACT with GLOBE advanced the assessment of economy-wide impacts of investments with feedback to agricultural incomes. However, additional disaggregation would further enrich the analysis. The analysis focuses on innovation investments in sustainable intensification of agricultural production, rather than on the full food system. Analysis of value chains could highlight important complementary interventions that could ensure there is full capacity throughout the value chain for the increased production modeled in this work. Hunger in this analysis is defined as the SDG 2.1 calorie-based target to end hunger. Future work should focus also on dietary and nutritional security and quality.

As with the other studies on ending hunger, we focus on calorie-based hunger. This afflicted 689 million people in 2019, an increase of 10 million from 2018 and of nearly 60 million from 2014 (FAO 2021b). Projections of other aspects of nutrition and food security, such as micronutrient malnutrition and childhood stunting are more complex, as is distributional analysis by groups of people within countries. It is likely that the cost of addressing these aspects of hunger in addition to calorie-based hunger would be considerably higher than the estimates here. As noted in Rosegrant et al. (2021), broader malnutrition problems, together with the continued transformation of food systems in developing countries, requires wider-ranging approaches and interventions to improving nutritional outcomes than have been used historically. Reducing the impact of these factors would require changes beyond the agricultural sector, including planning, transportation, public health, food production and marketing (Caballero 2007; Ruel et al. 2017). Interventions and policies should take account of the need for more sustainable diets that would include a sufficient supply of micronutrient-rich foods without excessive consumption of energy-dense, nutrient-poor foods (Kearney 2010). In promoting nutrition and health-driven policies, it will be important to target those most in need, particularly children and marginalized populations underserved by essential health services. Furthermore, filling the knowledge gaps through research, scaling innovation solutions and promoting partnerships across health, nutrition and agriculture will be important (Fan et al. 2019).

The potential gains from investment in agricultural R&D and water resources are susceptible to uncertainty in governance and the fragility of states. The SSPs focus their narratives on long-running trends in the global economy, which, while helpful for exploring scenarios around climate change and long-term drivers in the food system like agricultural R&D, do not include other drivers that are important to global food security. For example, extreme social and environmental events, such as the COVID-19 pandemic, will result in year-to-year variability and alter trajectories, at least in the short run. These events can displace millions while destroying human, physical, natural and social capital and limiting the capacity of societies to effectively function. Although the projections here do not assume effective or improved governance, a worsening of governance and conflict can slow the projected growth (Mason-D’Croz et al. 2019).

The focus of our GHG emissions analysis is on emissions in agriculture consistent with sustainable agriculture intensification trajectory for closing the investment gap. It does not focus on a food systems trajectory, including changes in cold storage and diets, or emissions from transportation, downstream processing of food, the manufacture of tractors and fertilizer or other relevant inputs. Emissions from these sources are included by IPCC guidelines in other, non-agricultural sectors such as transport and energy. Land use change and deforestation emissions driven by agriculture were accounted for to the extent that they are generated by the investments analyzed in this report.

In most analyses of technical options for mitigation that we draw upon here, some of the options have low or even negative costs in specific regions. This occurs when the net revenues associated with an option are positive, indicating that the practice would be profitable even in the absence of mitigation incentives such as carbon payments or targeted subsidies (Beach et al. 2015). It is therefore necessary to also address potential barriers that may need to be overcome to achieve adoption options that have low or negative costs, and that also hinder adoption of higher cost options even with mitigation incentives. These barriers may include institutional problems, lack of property rights, risk aversion among agricultural producers, market imperfections and regulatory or legal issues (Beach et al. 2015). Giller et al. (2009), for example, point to farm-level constraints to adoption of conservation tillage for soil sequestration in Africa. These include decreased yields often observed, increased labor requirements when herbicides are not used, a shift of the labor burden to women, limited access to external inputs, and a lack of mulch due to both low productivity and the priority given to feeding of livestock with crop residues.

Constraints can also arise in the implementation of carbon sequestration programs (Pannell 2021). Soil sequestration is a one-off process, with soil carbon increasing up to a new equilibrium level after about 20-30 years and then stopping. However, the adoption of the management regime needs to be maintained to avoid releasing the sequestered carbon; this means that while costs continue to be incurred, new benefits that would justify further payments do not. Additionality therefore needs to be determined, so that management options undertaken by farmers are additional to what they would do anyway. If they are not additional, then carbon payments will not contribute to climate change mitigation. Monitoring and measuring soil carbon stored in soils is also costly, requiring regular soil testing to confirm that carbon has been sequestered. Measurement is costlier when it needs to be done for multiple small farms. Innovations in measurement through advances in information and communications technologies (ICT), including less expensive soils and remote sensing, could help reduce the costs. Managing carbon sequestration for groups of farmers rather than individual farmers could also be more cost effective (Pannell 2021).

Annex 3. Discussion of supporting policies and investments

Agricultural value chains

Innovations and investments in the value chain will improve the prospects for meeting the SDG2, SDG6, SDG13 and Paris Agreement targets. Infrastructure investments, including in rural roads, electricity cell phone towers, markets, cold chains and processing facilities have important impacts on input and output markets. Innovations and investments in the value chain can make the outputs of agricultural R&D investments more profitable for farmers and generate higher social returns to agricultural R&D investments. Input and output market investments can reduce marketing margins and post-harvest losses of food, thereby generating substantial production and income gains and potentially significantly reducing hunger. It is likely that expanded investments in these items will require partnerships with the private sector. Aggregating mechanisms need to be put in place, for example, through cooperatives that can help ensure that economies of scale for inspection, packaging, food safety regimes and quality management are achieved competitively. Such cooperatives can also lower costs for agricultural inputs such as seeds and chemicals and can also support microfinance services.

Farmers need timely and reliable information about markets. In addition to information on prices, a whole range of business-related information is essential, such as who the buyers are and what their terms and conditions for doing business are. Market information services have often suffered from problems related to the timeliness and accuracy of the information provided. Digital information systems linked to farmer mobile phones can increase access to timely information, improve links between farmers and processors, and reduce transport costs, thereby reducing post-harvest losses. (USAID 2017). In addition to market information services, advanced digital technologies – such as satellite imaging, remote sensing and in-field sensors – can support precision farming based on observation of, and response to, intra-field variations that guide the efficient application of inputs and improve productivity and farm income. However, there are many constraints to raising funds for advanced technologies to benefit small farmers and improve input and output markets in the value chain, and solving these constraints may require innovations in financial instruments and approaches.

Finance

Among other constraints, low agricultural productivity in the Global South is related to smallholder farmers’ lack of capital and access to affordable credit. The unmet demand for smallholder finance is considerable: the credit gap for smallholder farmers in the Global South is estimated at about USD 170 billion per year (Initiative for Smallholder Finance 2019). In the past two decades there has been a decline in the provision of agricultural finance for smallholders by governments in many parts of the world. In some cases, this gap has been replaced by credit cooperatives, microfinance institutions, finance through the value chain by contract farming arrangements, and, occasionally, by commercial banks. Nevertheless, access to financial services by smallholders remains limited (Committee on

Agriculture 2010). IFPRI (2021, forthcoming), compares access to financial services between country groups in relation to the performance in poverty and malnutrition alleviation, and find that access to financial institutions is associated with effective poverty alleviation. The links between access to financial institutions and reduction of undernourishment are weaker, although access to credit or borrowing money from a financial institution is related to better performance in poverty alleviation.

The importance of access to financial services is indicative of the importance of private sector investments in meeting the investment targets, but significant constraints have held back private participation in the agricultural sector. Investments in agriculture compete with other sectors based on the attractiveness of the risk-return profile. This depends on a stable revenue stream and how the range of risks related to agricultural investments are shared between the public and private actors. Several factors have inhibited private sector investment in agriculture, including relatively low rates of return and perceived high financial risks due to the uncertainty in returns in the agricultural sector (Svendsen et al. 2003). Several financial mechanisms for investment in agriculture are promising. These include green and blue bonds, payment for ecosystem services, and blended public and private finance. Blended finance, which strategically uses development finance or public funding to mobilize additional finance towards sustainable development in the Global South, is a promising approach to scale up private sector financing for water (OECD 2018).

Extension

The quality of the extension system is an important factor in supporting the adoption and effectiveness of new technologies, potentially increasing the benefits of the investment analyzed here. Extension services in the Global South have changed significantly over the past four decades, increasingly moving from a traditional emphasis on technology transfer and farm management information, supplied by the public sector, to a broader public and private advisory service model with increasing participation of the private sector (dealing with agricultural inputs agribusiness, and financial services), non-governmental organizations, producer groups, cooperatives and associations, and ICT services (Blum et al. 2020, cited in IFPRI 2021, forthcoming). Further expansion of extension services into marketing, food safety, and the establishment of closer links with agri-food industries and related areas would be beneficial (Committee on Agriculture 2010). Social networks and farmer-to-farmer extension have been growing in Africa, and evidence shows that they increase the effectiveness of extension (Takahashi et al. 20209). A cross-country analysis of extension services shows that the best performing countries in poverty alleviation have better education facilities, a greater focus by extension services on natural resources and climate change, and prioritize women and young adult farmers. In the case of malnutrition, the key difference between groups of performance is that best performing countries prioritize rural women in the areas of nutrition and health (IFPRI 2021, forthcoming).

Gender-responsive policies and investments

Achieving global food security and nutrition, promoting sustainable agriculture and addressing climate change are inextricably linked with gender equality and women’s empowerment. If gender is not adequately considered in agricultural R&D systems as well as extension and other information dissemination, it will be impossible to meet the food needs of future populations or ensure that agricultural productivity translates into improved welfare for the poor. As such, gender equity in agricultural R&D systems is a matter of development effectiveness that can benefit women, men and their families alike (Bryan and Garner 2020; Meinzen-Dick et al. 2011). Beyond access to resources and information, it is important that women scientists also participate more actively in agricultural research development. Although female participation in agricultural research has improved in recent years, Beintema and Stads (2017) report that women remain less likely to hold research management positions than their male colleagues in much of sub-Saharan Africa, for example. As a result, women have less influence in policy- and decision-making processes, making it challenging to reflect gendered needs at the outset of the technology generation process.

While progress in reducing gender gaps in agriculture have been made, and women comprise a significant share of the agricultural labor force, they continue to have less access to productive resources, including land, labor and irrigation water, to new technologies and to services like information and financial services. Women also have less decision-making authority and fewer opportunities given their combined domestic and productive responsibilities (Bryan and Garner 2020; Blackmore 2021). In addition to policies and investments to increase women's access to a range of resources and services, cultural power imbalances and intra-household dynamics that limit women's decision-making agency should be addressed (Blackmore et al. 2018; FAO 2019).

Evidence shows that increasing women's access to land, financial and natural resources and information, in addition to a more equitable distribution of new technology, could positively impact women's ability to produce and gain access to food. This, in turn, can positively impact the nutritional status of the entire household (Agarwal 2018; Lodin et al. 2014; Blackmore 2021). Bryan et al. (2021) finds that gendered differences in awareness and adoption of climate smart agricultural practices in southwestern Bangladesh were linked with low access to key information sources by women farmers. Moreover, women were more likely than men to adopt some climate smart practices, particularly those related to their gendered roles, such as improved livestock feeding practices and grain storage, when they became aware of adaptation options. The results suggest that greater efforts to reach both men and women with information on climate smart agriculture would increase awareness and adoption of climate smart practices. A further study, by de Pinto et al. (2020), also from Bangladesh, finds that that increased women's empowerment, measured using the Women's Empowerment in Agriculture Index, leads to increased diversification in the use of farmland, including a transition from cereal production to other crops like vegetables and fruits. Meinzen-Dick et al. (2011) further summarize the voluminous evidence of the beneficial impacts of policies and investment that improve women's access to resources on adoption and diffusion of seed technology, the effectiveness of irrigation, the nutritional status of children and many other important outcomes.

Social protection

Broad social protection coverage includes assistance through cash transfers to those who need them, especially children; benefits and support for people of working age in case of maternity, disability, work injury or for those without jobs; and pension coverage for the elderly. Assistance can be provided through targeted cash transfers, social insurance, tax-funded social benefits, social assistance services, public works programs, among others (World Bank 2012). Social protection systems, programs and policies contribute to improved food security by raising incomes, and thus purchasing power, which improves access to more nutritious diets and food use. In the short term, public investment in social protection can also close the poverty gap and increase incomes, both directly and through increased productivity. In the long run, investments in social protection innovation investments will be mutually reinforcing and sustaining (FAO et al. 2015). By providing basic income support to the poor, social protection systems also help disadvantaged people take advantage of opportunities to improve their livelihoods and recover from shocks and adverse events (World Bank 2012). When properly designed, these programs can support more productive and potentially more diversified livelihoods. They can also help people participate in the growth process by taking advantage of the investments in sustainable intensification, such as those analyzed in this paper (Cervigni and Morris 2016).

Water management

The impacts of the investments in improved water management and water use efficiency that are assessed in the IMPACT scenarios and in the technical options for climate mitigation, such as advanced irrigation, integrated soil and water management, and precision farming, would be facilitated by reforms in water management. In addition to the potential to generate water savings, such reforms would provide substantial benefits from increased income from higher value crops, convenience in farming operations, reducing labor use and reduced pumping costs. Beyond individual farmers, however, real system-wide water savings are difficult to achieve and often limited due to the nature of water flows and distributions in river basins. New technologies can save water that would otherwise evaporate unproductively or flow to sinks, providing net system water savings. However, it can also consume water that would otherwise be used downstream; shift water use between farmers, rather than generating new benefits; and can even induce increased water use by increasing the profitability of irrigation for individual farmers (Perry et al. 2009; Molden et al. 2010).

The potential benefits from advanced technologies and the larger benefits from water allocation improvement can be achieved using incentives, regulations, institutional reform and investments in water management. An important step underlying much of the needed actions is the establishment of water rights vested in users and/or user groups. Water rights provide incentives for investment in technology improvements and water management, as farmers know they can retain water rights when investing in farm improvement, new crop varieties, improved irrigation technology and crop management (Rosegrant 2020). Well-specified water rights can also establish a cap on water use and provide the incentives to optimize the economic value of water (Young 2015; Young and McColl 2009).

Devolution of important sub-basin water management functions to community-based water user associations (WUAs), farmer groups or other private sector actors can also be beneficial. However, institutional approaches need to be pragmatic in seeking solutions that are effective within the physical, social and governance context of specific locations. Similarly, WUAs are more likely to be effective when the design and implementation of the WUA involves prospective members; when the provision of improved water delivery services is emphasized, rather than just farmer obligations such as fee payments; and when the WUA has the right to make and enforce water allocation rules and sanctions (Aarnoudse et al. 2018; Araral 2005).

Carbon payments and smart subsidies

The analysis of technical options for GHG emissions mitigation showed that a carbon price of USD 70/tCO_2eq could result in a reduction of non-CO_2 emissions that is consistent with a 2°C climate change pathway and that meets some of the targets for a 1.5°C pathway. Carbon payments and other target smart subsidies have the potential to incentivize specific goals, such as carbon mitigation and the promotion of environmental services. In addition to carbon payments, these subsidies could come in the form of loans or targeted subsidized prices on equipment for smallholder farmers to invest in improved practices such as drip irrigation. Smart subsidies could also cover labor and installation costs for water harvesting structures. Temporary subsidies during the early stage of input and technology adoption may be effective in overcoming the fixed costs related to the adoption of new technology. They may also be effective in inducing farmer experimentation and learning during periods of rapidly changing technological potential. Such smart subsidies should be temporary and phased out as adoption and appropriate use of technologies become widespread. However, the phase out of subsidies becomes difficult once they are established and develop political support, so care must be taken in implementation (Goyal and Nash 2017; Rosegrant 2019).

Broader payments for environmental services (PES) can further boost the benefits or the investments analyzed in this paper. These payments can be made to farmers or landowners who agree to manage their land or watersheds for environmental protection; protect water resources; reduce greenhouse gas emissions; or improve soil quality and nutrient status. Most PES programs have focused on reducing deforestation or watershed improvement. Meta-reviews of PES evaluations show that PES programs have not performed as well as expected at implementation but have in some cases achieved moderate reductions in deforestation. Significant positive impacts on environmental outcomes have been found primarily for PES at local or sub-national scale. Small-scale user-financed programs with effective targeting criteria and strong conditionality rules have generally performed better. Other factors associated with success of PES include low opportunity costs on other uses of the land, or payments high enough to cover the opportunity costs; limited mobility of production factors; and well-established property rights. Appropriate monitoring and sanctioning mechanisms and social safeguards would also increase the probability of success. (Börner et al. 2017; Naeem et al. 2015; Gaworecki 2017). Thus, PES is most likely to succeed when there is a clear demand for environmental services that have financial value to one or more stakeholders; the services needed are feasible; there are effective brokers or intermediaries; land and water rights are clear; contracts can be enforced; and the outcomes can be independently monitored and evaluated.

Implementation of carbon payments and smart subsidies would be promoted by a reduction of fertilizer, water, energy, and fertilizer subsidies that distort production decisions and cause overuse of fertilizer, water, and other inputs, resulting in excess carbon emissions and environmental degradation. These subsidies are politically difficult to remove, but their removal could be more palatable if the resulting budget savings were invested in compensatory income support to small farmers, carbon payments and other targeted smart subsidies to achieve specific sustainability goals.

Agroecological and landscape approaches

Many interventions that support sustainable agriculture intensification are addressed in this report, including investments in agricultural R&D that reduce pressure on crop area and deforestation; water resource investments that reduce agricultural water use and improve agricultural water quality; climate smart and resource-conserving technologies and farming systems, such as crop rotation and cover crops; conservation tillage and residue management; improved water management through precision agriculture and water harvesting; improved pasture management use of legumes; and improved manure management systems in livestock systems. In addition to the impacts on climate mitigation assessed here, many of these practices can contribute to biodiversity, improved soil quality such as soil organic content, and reduced soil erosion (Smith et al. 2018) Smith et al. 2014).

Broader and interrelated approaches, including agroecological systems, ecosystem-based adaptation and integrated landscape management can further improve these outcomes of sustainable agriculture intensification. Agroecological systems are integrated land use systems that maintain species diversity in a range of productive niches, enhance ecological processes and deliver ecosystem services (Mbow et al. 2019). Nie et al. (2016) argued that while integrated crop-livestock systems present some opportunities, such as control of weeds, pests and diseases, and environmental benefits, they potentially result in yield reduction and the development of persistent weeds and pests (cited in Mbow et al. 2019). But other studies find that increasing and conserving biological diversity can promote higher crop yields while sustaining the environment (Schmitz et al. 2015; Bhattacharyya et al. 2016; Garibaldi et al. 2017).

Ecosystem-based adaptation is a set of nature-based methods that can provide co-benefits such as contributions to health and improved diet, sustainable land management, economic revenue and water security (Mbow et al. 2019). For example, agroforestry systems can contribute to improving food productivity while enhancing biodiversity conservation, ecological balance and restoration under changing climate conditions (Mbow et al. 2014; Paudel et al. 2017; Newaj et al. 2016; Altieri et al. 2015, cited in Mbow et al. 2019).

Integrated landscape management, which involves voluntary collaboration among multiple stakeholders from different sectors and social groups, is a process for achieving sustainable landscapes and inclusive rural transformation. Shames et al. (2017) outline how government action and policy can support integrated landscape management by promoting “joint investment planning among stakeholders, developing market and trade rules supportive of landscape-scale action, mobilizing private demand for ecosystem services, developing fiscal and tax policy to incentivize landscape investments, and developing screening criteria for landscape investments, allocating public revenues for integrated landscape programs, and influencing donor priorities and investments.”

Annex 4. Summary of key parameters in IMPACT

The parameters summarized here are defined at the national or sub-national level. The values here are the range of the values for national-level values (or sub-national level aggregated to national) for individual countries within each region.

Table A4.1. Own-price elasticities of demand.

Region	Commodity	Min (2030)	Max (2030)
EAP	Beans	-0.29	-0.10
EAP	Cassava	-0.22	-0.05
EAP	Groundnut	-0.27	-0.08
EAP	Maize	-0.33	-0.09
EAP	Pork	-0.42	-0.16
EAP	Potato	-0.44	-0.19
EAP	Poultry	-0.35	-0.11
EAP	Rice	-0.39	-0.13
EAP	Temperate Fruit	-0.89	-0.24
EAP	Tropical Fruit	-0.41	-0.15
EAP	Vegetables	-0.39	-0.15
EAP	Wheat	-0.38	-0.24
EUR	Beans	-0.25	-0.08
EUR	Cassava	-0.19	-0.06
EUR	Groundnut	-0.23	-0.09
EUR	Maize	-0.24	-0.10
EUR	Pork	-0.39	-0.09
EUR	Potato	-0.30	-0.14
EUR	Poultry	-0.23	-0.21
EUR	Rice	-0.37	-0.24
EUR	Temperate Fruit	-0.35	-0.23
EUR	Tropical Fruit	-0.36	-0.20
EUR	Vegetables	-0.32	-0.23
EUR	Wheat	-0.26	-0.20
FSU	Beans	-0.10	-0.07
FSU	Cassava	-0.09	-0.05
FSU	Groundnut	-0.09	-0.06
FSU	Maize	-0.11	-0.09
FSU	Pork	-0.35	-0.32
FSU	Potato	-0.29	-0.18
FSU	Poultry	-0.23	-0.20
FSU	Rice	-0.30	-0.27
FSU	Temperate Fruit	-0.35	-0.17
FSU	Tropical Fruit	-0.26	-0.19

FSU	Vegetables	-0.34	-0.29
FSU	Wheat	-0.23	-0.20
LAC	Beans	-0.22	-0.16
LAC	Cassava	-0.17	-0.10
LAC	Groundnut	-0.19	-0.14
LAC	Maize	-0.24	-0.14
LAC	Pork	-0.46	-0.24
LAC	Potato	-0.34	-0.20
LAC	Poultry	-0.30	-0.27
LAC	Rice	-0.33	-0.23
LAC	Temperate Fruit	-0.40	-0.24
LAC	Tropical Fruit	-0.36	-0.16
LAC	Vegetables	-0.37	-0.17
LAC	Wheat	-0.32	-0.18
MEN	Beans	-0.34	-0.11
MEN	Cassava	-0.34	-0.11
MEN	Groundnut	-0.34	-0.08
MEN	Maize	-0.38	-0.11
MEN	Pork	-0.41	-0.08
MEN	Potato	-0.41	-0.20
MEN	Poultry	-0.30	-0.21
MEN	Rice	-0.44	-0.24
MEN	Temperate Fruit	-0.47	-0.18
MEN	Tropical Fruit	-0.40	-0.26
MEN	Vegetables	-0.40	-0.23
MEN	Wheat	-0.46	-0.20
NAM	Beans	-0.25	-0.22
NAM	Cassava	-0.12	-0.10
NAM	Groundnut	-0.21	-0.20
NAM	Maize	-0.23	-0.19
NAM	Pork	-0.29	-0.25
NAM	Potato	-0.29	-0.20
NAM	Poultry	-0.24	-0.19
NAM	Rice	-0.39	-0.37
NAM	Temperate Fruit	-0.35	-0.24
NAM	Tropical Fruit	-0.40	-0.37
NAM	Vegetables	-0.39	-0.39
NAM	Wheat	-0.28	-0.24
SAS	Beans	-0.28	-0.16
SAS	Cassava	-0.20	-0.14
SAS	Groundnut	-0.26	-0.13
SAS	Maize	-0.27	-0.14
SAS	Pork	-0.42	-0.08
SAS	Potato	-0.47	-0.30
SAS	Poultry	-0.25	-0.19

SAS	Rice	-0.26	-0.23
SAS	Temperate Fruit	-0.53	-0.39
SAS	Tropical Fruit	-0.35	-0.30
SAS	Vegetables	-0.39	-0.31
SAS	Wheat	-0.44	-0.22
SSA	Beans	-0.34	-0.16
SSA	Cassava	-0.38	-0.11
SSA	Groundnut	-0.34	-0.14
SSA	Maize	-0.39	-0.14
SSA	Pork	-0.41	-0.24
SSA	Potato	-0.45	-0.12
SSA	Poultry	-0.30	-0.24
SSA	Rice	-0.46	-0.27
SSA	Temperate Fruit	-0.44	-0.17
SSA	Tropical Fruit	-0.41	-0.16
SSA	Vegetables	-0.38	-0.17
SSA	Wheat	-0.46	-0.25

Table A4.2. Income elasticity of demand.

Region	Commodity	Min (2030)	Max (2030)
EAP	Beans	0.12	0.29
EAP	Beef	0.15	0.88
EAP	Cassava	-0.50	0.13
EAP	Groundnut	0.00	0.10
EAP	Maize	-0.11	0.32
EAP	Pork	0.06	0.99
EAP	Potato	0.00	0.57
EAP	Poultry	0.27	0.93
EAP	Rice	-0.19	0.40
EAP	Temperate Fruit	0.20	0.62
EAP	Tropical Fruit	0.21	0.75
EAP	Vegetables	0.11	0.65
EAP	Wheat	0.11	0.50
EUR	Beans	0.14	0.21
EUR	Beef	0.11	0.25
EUR	Cassava	-0.30	0.10
EUR	Groundnut	0.00	0.12
EUR	Maize	-0.10	0.30
EUR	Pork	0.03	0.24
EUR	Potato	-0.10	0.00
EUR	Poultry	0.34	0.54
EUR	Rice	0.00	0.32
EUR	Temperate Fruit	0.21	0.37
EUR	Tropical Fruit	0.00	0.54

EUR	Vegetables	0.16	0.33
EUR	Wheat	0.07	0.38
FSU	Beans	0.09	0.18
FSU	Beef	0.05	0.45
FSU	Cassava	-0.31	0.10
FSU	Groundnut	0.00	0.12
FSU	Maize	-0.10	0.10
FSU	Pork	0.23	0.47
FSU	Potato	-0.10	0.25
FSU	Poultry	0.47	0.76
FSU	Rice	0.13	0.34
FSU	Temperate Fruit	0.20	0.40
FSU	Tropical Fruit	0.30	0.55
FSU	Vegetables	0.15	0.40
FSU	Wheat	0.07	0.19
LAC	Beans	0.18	0.26
LAC	Beef	0.06	0.61
LAC	Cassava	-0.20	0.10
LAC	Groundnut	0.00	0.05
LAC	Maize	0.02	0.17
LAC	Pork	0.15	0.99
LAC	Potato	0.05	0.32
LAC	Poultry	0.31	0.93
LAC	Rice	-0.04	0.22
LAC	Temperate Fruit	0.16	0.49
LAC	Tropical Fruit	0.09	0.50
LAC	Vegetables	0.36	0.49
LAC	Wheat	0.07	0.34
MEN	Beans	0.15	0.31
MEN	Beef	0.03	0.72
MEN	Cassava	-0.20	0.10
MEN	Groundnut	0.00	0.08
MEN	Maize	0.00	0.31
MEN	Pork	-0.12	0.79
MEN	Potato	0.00	0.38
MEN	Poultry	0.07	0.71
MEN	Rice	0.01	0.44
MEN	Temperate Fruit	-0.06	0.45
MEN	Tropical Fruit	0.00	0.63
MEN	Vegetables	0.14	0.53
MEN	Wheat	-0.06	0.37
NAM	Beans	0.14	0.15
NAM	Beef	-0.03	0.03
NAM	Cassava	-0.31	-0.20
NAM	Groundnut	0.00	0.00

NAM	Maize	0.07	0.32
NAM	Pork	-0.12	0.05
NAM	Potato	0.00	0.09
NAM	Poultry	0.32	0.53
NAM	Rice	0.09	0.43
NAM	Temperate Fruit	0.24	0.36
NAM	Tropical Fruit	0.28	0.37
NAM	Vegetables	0.39	0.66
NAM	Wheat	0.07	0.35
SAS	Beans	0.13	0.27
SAS	Beef	0.33	0.81
SAS	Cassava	-0.06	0.10
SAS	Groundnut	0.00	0.06
SAS	Maize	0.13	0.21
SAS	Pork	0.26	0.56
SAS	Potato	0.15	0.48
SAS	Poultry	0.42	1.15
SAS	Rice	-0.14	0.19
SAS	Temperate Fruit	0.46	0.87
SAS	Tropical Fruit	0.39	0.95
SAS	Vegetables	0.25	0.86
SAS	Wheat	0.09	0.40
SSA	Beans	0.14	0.30
SSA	Beef	0.17	0.91
SSA	Cassava	-0.16	0.26
SSA	Groundnut	0.00	0.17
SSA	Maize	-0.11	0.42
SSA	Pork	0.00	1.15
SSA	Potato	0.00	0.80
SSA	Poultry	0.38	1.03
SSA	Rice	0.02	0.68
SSA	Temperate Fruit	0.11	0.78
SSA	Tropical Fruit	0.13	0.92
SSA	Vegetables	0.14	0.96
SSA	Wheat	0.11	0.80

Table A4.3. Yield elasticity with respect to commodity price.

Region	Commodity	Min	Max
EAP	Beans	0.13	0.24
EAP	Cassava	0.05	0.11
EAP	Groundnut	0.07	0.12
EAP	Maize	0.08	0.16
EAP	Potato	0.14	0.28
EAP	Rice	0.08	0.14

EAP	Temperate Fruit	0.10	0.17
EAP	Tropical Fruit	0.12	0.21
EAP	Vegetables	0.13	0.45
EAP	Wheat	0.10	0.17
EUR	Beans	0.17	0.20
EUR	Cassava	0.07	0.11
EUR	Groundnut	0.08	0.10
EUR	Maize	0.11	0.15
EUR	Potato	0.18	0.22
EUR	Rice	0.10	0.11
EUR	Temperate Fruit	0.11	0.13
EUR	Tropical Fruit	0.13	0.15
EUR	Vegetables	0.15	0.18
EUR	Wheat	0.11	0.23
FSU	Beans	0.18	0.26
FSU	Cassava	0.10	0.13
FSU	Groundnut	0.09	0.13
FSU	Maize	0.13	0.19
FSU	Potato	0.20	0.30
FSU	Rice	0.10	0.14
FSU	Temperate Fruit	0.11	0.16
FSU	Tropical Fruit	0.14	0.19
FSU	Vegetables	0.16	0.23
FSU	Wheat	0.11	0.16
LAC	Beans	0.12	0.24
LAC	Cassava	0.05	0.11
LAC	Groundnut	0.06	0.12
LAC	Maize	0.08	0.15
LAC	Potato	0.14	0.28
LAC	Rice	0.11	0.17
LAC	Temperate Fruit	0.09	0.17
LAC	Tropical Fruit	0.11	0.20
LAC	Vegetables	0.13	0.24
LAC	Wheat	0.09	0.17
MEN	Beans	0.17	0.26
MEN	Cassava	0.07	0.13
MEN	Groundnut	0.08	0.13
MEN	Maize	0.11	0.16
MEN	Potato	0.20	0.32
MEN	Rice	0.11	0.17
MEN	Temperate Fruit	0.13	0.18
MEN	Tropical Fruit	0.15	0.22
MEN	Vegetables	0.18	0.47
MEN	Wheat	0.13	0.18
NAM	Beans	0.18	0.23

NAM	Cassava	0.07	0.11
NAM	Groundnut	0.09	0.11
NAM	Maize	0.16	0.21
NAM	Potato	0.20	0.26
NAM	Rice	0.11	0.13
NAM	Temperate Fruit	0.12	0.14
NAM	Tropical Fruit	0.14	0.17
NAM	Vegetables	0.17	0.20
NAM	Wheat	0.12	0.14
SAS	Beans	0.22	0.28
SAS	Cassava	0.10	0.13
SAS	Groundnut	0.11	0.14
SAS	Maize	0.13	0.17
SAS	Potato	0.26	0.32
SAS	Rice	0.10	0.14
SAS	Temperate Fruit	0.16	0.20
SAS	Tropical Fruit	0.19	0.24
SAS	Vegetables	0.22	0.52
SAS	Wheat	0.16	0.25
SSA	Beans	0.22	0.32
SSA	Cassava	0.11	0.16
SSA	Groundnut	0.11	0.16
SSA	Maize	0.13	0.20
SSA	Potato	0.26	0.38
SSA	Rice	0.13	0.21
SSA	Temperate Fruit	0.14	0.23
SSA	Tropical Fruit	0.17	0.27
SSA	Vegetables	0.20	0.32
SSA	Wheat	0.14	0.23

Table A4.4. Yield elasticity with respect to input prices.

Region	Commodity	Min of FERT	Max of FERT	Min of wage	Max of wage
EAP	Beans	-0.10	-0.01	-0.09	-0.01
EAP	Cassava	-0.05	-0.03	-0.09	-0.02
EAP	Groundnut	-0.10	-0.01	-0.09	-0.01
EAP	Maize	-0.06	-0.03	-0.11	-0.02
EAP	Potato	-0.05	-0.03	-0.11	-0.02
EAP	Rice	-0.06	-0.03	-0.10	-0.02
EAP	Temperate Fruit	-0.06	0.00	-0.06	-0.01
EAP	Tropical Fruit	-0.07	0.00	-0.07	-0.01
EAP	Vegetables	-0.08	0.00	-0.08	-0.01
EAP	Wheat	-0.06	-0.03	-0.12	-0.02
EUR	Beans	-0.07	-0.02	-0.07	-0.01
EUR	Cassava	-0.04	-0.03	-0.08	-0.03

EUR	Groundnut	-0.07	-0.02	-0.07	-0.01
EUR	Maize	-0.06	-0.04	-0.09	-0.04
EUR	Potato	-0.05	-0.03	-0.08	-0.03
EUR	Rice	-0.05	-0.04	-0.07	-0.03
EUR	Temperate Fruit	-0.04	-0.02	-0.04	-0.02
EUR	Tropical Fruit	-0.05	-0.02	-0.05	-0.02
EUR	Vegetables	-0.06	-0.03	-0.06	-0.02
EUR	Wheat	-0.05	-0.04	-0.08	-0.03
FSU	Beans	-0.07	-0.02	-0.10	-0.03
FSU	Cassava	-0.04	-0.03	-0.10	-0.08
FSU	Groundnut	-0.07	-0.02	-0.10	-0.03
FSU	Maize	-0.06	-0.04	-0.13	-0.08
FSU	Potato	-0.04	-0.03	-0.11	-0.07
FSU	Rice	-0.05	-0.04	-0.10	-0.07
FSU	Temperate Fruit	-0.03	-0.02	-0.06	-0.04
FSU	Tropical Fruit	-0.03	-0.02	-0.07	-0.04
FSU	Vegetables	-0.04	-0.03	-0.08	-0.05
FSU	Wheat	-0.05	-0.04	-0.11	-0.07
LAC	Beans	-0.04	-0.03	-0.08	-0.03
LAC	Cassava	-0.03	-0.03	-0.09	-0.03
LAC	Groundnut	-0.04	-0.03	-0.08	-0.03
LAC	Maize	-0.05	-0.04	-0.10	-0.04
LAC	Potato	-0.04	-0.04	-0.11	-0.04
LAC	Rice	-0.05	-0.04	-0.11	-0.04
LAC	Temperate Fruit	-0.03	-0.02	-0.06	-0.02
LAC	Tropical Fruit	-0.04	-0.03	-0.07	-0.03
LAC	Vegetables	-0.05	-0.03	-0.08	-0.03
LAC	Wheat	-0.06	-0.04	-0.11	-0.04
MEN	Beans	-0.10	-0.01	-0.12	-0.02
MEN	Cassava	-0.05	-0.03	-0.13	-0.05
MEN	Groundnut	-0.10	-0.01	-0.12	-0.02
MEN	Maize	-0.06	-0.03	-0.14	-0.05
MEN	Potato	-0.05	-0.03	-0.14	-0.05
MEN	Rice	-0.06	-0.03	-0.14	-0.05
MEN	Temperate Fruit	-0.05	-0.01	-0.08	-0.03
MEN	Tropical Fruit	-0.05	-0.01	-0.10	-0.03
MEN	Vegetables	-0.06	-0.01	-0.11	-0.04
MEN	Wheat	-0.06	-0.03	-0.16	-0.05
NAM	Beans	-0.10	-0.08	-0.02	-0.01
NAM	Cassava	-0.05	-0.03	-0.05	-0.01
NAM	Groundnut	-0.10	-0.08	-0.02	-0.01
NAM	Maize	-0.05	-0.03	-0.06	-0.01
NAM	Potato	-0.05	-0.03	-0.05	-0.01
NAM	Rice	-0.05	-0.03	-0.05	-0.01
NAM	Temperate Fruit	-0.05	-0.05	-0.03	-0.01

NAM	Tropical Fruit	-0.07	-0.05	-0.03	-0.01
NAM	Vegetables	-0.08	-0.06	-0.04	-0.01
NAM	Wheat	-0.05	-0.03	-0.05	-0.01
SAS	Beans	-0.05	-0.02	-0.10	-0.07
SAS	Cassava	-0.04	-0.03	-0.10	-0.07
SAS	Groundnut	-0.05	-0.02	-0.10	-0.07
SAS	Maize	-0.05	-0.04	-0.13	-0.08
SAS	Potato	-0.05	-0.03	-0.11	-0.08
SAS	Rice	-0.05	-0.04	-0.09	-0.05
SAS	Temperate Fruit	-0.04	-0.02	-0.07	-0.04
SAS	Tropical Fruit	-0.05	-0.02	-0.08	-0.05
SAS	Vegetables	-0.06	-0.03	-0.09	-0.06
SAS	Wheat	-0.06	-0.04	-0.13	-0.08
SSA	Beans	-0.10	-0.01	-0.15	-0.02
SSA	Cassava	-0.05	-0.03	-0.16	-0.05
SSA	Groundnut	-0.10	-0.01	-0.15	-0.02
SSA	Maize	-0.05	-0.03	-0.18	-0.06
SSA	Potato	-0.05	-0.03	-0.18	-0.05
SSA	Rice	-0.05	-0.03	-0.19	-0.05
SSA	Temperate Fruit	-0.05	-0.01	-0.10	-0.03
SSA	Tropical Fruit	-0.05	-0.01	-0.12	-0.03
SSA	Vegetables	-0.06	-0.01	-0.14	-0.04
SSA	Wheat	-0.05	-0.03	-0.20	-0.05

Note: FERT: elasticity of yield with respect to fertilizer price.

Table A4.5. Area elasticities with respect to commodity price.

Region	Commodity	Min of air	Max of air	Min of arf	Max of arf
EAP	Beans	0.36	1.25	0.27	1.04
EAP	Cassava	0.02	0.31	0.02	0.24
EAP	Groundnut	0.46	0.84	0.35	0.70
EAP	Maize	0.34	0.84	0.24	0.63
EAP	Potato	0.26	0.55	0.20	0.41
EAP	Rice	0.26	0.70	0.18	0.58
EAP	Temperate Fruit	0.14	0.60	0.11	0.45
EAP	Tropical Fruit	0.36	0.55	0.27	0.44
EAP	Vegetables	0.48	0.82	0.36	0.68
EAP	Wheat	0.22	0.86	0.16	0.70
EUR	Beans	0.91	1.56	0.76	1.30
EUR	Cassava	0.02	0.34	0.02	0.25
EUR	Groundnut	0.60	1.04	0.50	0.86
EUR	Maize	0.63	0.84	0.63	0.70
EUR	Potato	0.43	0.58	0.36	0.48
EUR	Rice	0.62	0.96	0.47	0.80
EUR	Temperate Fruit	0.40	0.62	0.40	0.52

EUR	Tropical Fruit	0.34	0.65	0.34	0.54
EUR	Vegetables	0.61	0.84	0.56	0.70
EUR	Wheat	0.62	0.89	0.47	0.74
FSU	Beans	0.91	1.21	0.68	0.91
FSU	Cassava	0.02	0.12	0.02	0.09
FSU	Groundnut	0.60	0.81	0.45	0.60
FSU	Maize	0.66	0.84	0.50	0.63
FSU	Potato	0.36	0.58	0.27	0.43
FSU	Rice	0.53	0.96	0.40	0.72
FSU	Temperate Fruit	0.46	0.53	0.34	0.40
FSU	Tropical Fruit	0.46	0.65	0.34	0.49
FSU	Vegetables	0.65	0.82	0.49	0.61
FSU	Wheat	0.73	0.84	0.55	0.63
LAC	Beans	0.68	1.46	0.55	1.08
LAC	Cassava	0.14	0.42	0.12	0.31
LAC	Groundnut	0.46	0.97	0.38	0.72
LAC	Maize	0.39	1.27	0.32	0.95
LAC	Potato	0.26	0.81	0.22	0.58
LAC	Rice	0.33	1.56	0.27	1.17
LAC	Temperate Fruit	0.24	0.65	0.20	0.49
LAC	Tropical Fruit	0.33	0.82	0.27	0.61
LAC	Vegetables	0.44	0.89	0.36	0.67
LAC	Wheat	0.40	1.03	0.32	0.86
MEN	Beans	0.95	1.45	0.79	1.12
MEN	Cassava	0.02	0.39	0.02	0.30
MEN	Groundnut	0.63	0.97	0.53	0.74
MEN	Maize	0.42	0.84	0.35	0.70
MEN	Potato	0.41	0.60	0.31	0.46
MEN	Rice	0.36	0.86	0.30	0.65
MEN	Temperate Fruit	0.34	0.60	0.26	0.50
MEN	Tropical Fruit	0.44	0.62	0.34	0.52
MEN	Vegetables	0.60	0.89	0.45	0.67
MEN	Wheat	0.52	0.86	0.39	0.72
NAM	Beans	1.08	1.41	1.08	1.21
NAM	Cassava	0.03	0.19	0.02	0.19
NAM	Groundnut	0.72	0.94	0.72	0.81
NAM	Maize	0.99	1.58	0.84	1.58
NAM	Potato	0.34	0.64	0.34	0.55
NAM	Rice	0.31	0.94	0.26	0.94
NAM	Temperate Fruit	0.60	0.70	0.60	0.60
NAM	Tropical Fruit	0.53	0.65	0.46	0.65
NAM	Vegetables	0.89	0.90	0.77	0.89
NAM	Wheat	0.82	1.01	0.82	0.86
SAS	Beans	0.39	0.95	0.39	0.95
SAS	Cassava	0.14	0.36	0.14	0.36

SAS	Groundnut	0.49	0.63	0.37	0.63
SAS	Maize	0.29	0.87	0.22	0.87
SAS	Potato	0.41	0.58	0.36	0.58
SAS	Rice	0.43	0.64	0.32	0.62
SAS	Temperate Fruit	0.36	0.43	0.27	0.43
SAS	Tropical Fruit	0.41	0.53	0.36	0.53
SAS	Vegetables	0.48	0.62	0.36	0.62
SAS	Wheat	0.43	0.65	0.32	0.65
SSA	Beans	0.55	1.90	0.55	1.12
SSA	Cassava	0.02	0.55	0.02	0.36
SSA	Groundnut	0.38	1.27	0.38	0.74
SSA	Maize	0.28	1.16	0.32	0.73
SSA	Potato	0.22	0.84	0.22	0.46
SSA	Rice	0.24	0.91	0.18	0.63
SSA	Temperate Fruit	0.20	0.70	0.20	0.52
SSA	Tropical Fruit	0.27	0.95	0.27	0.52
SSA	Vegetables	0.36	1.31	0.36	0.72
SSA	Wheat	0.32	1.22	0.32	0.67

Note: air: irrigated crops; arf: rainfed crops.

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