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REVIEW

PUBLIC INVESTMENT IN AGRI-FOOD SYSTEM INNOVATION FOR SUSTAINABLE DEVELOPMENT

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KEYWORDS

agri-food system, innovation, R&D investment, productivity, climate change

HIGHLIGHTS

- Global public and private agricultural R&D spending has increased since 2000.
- Agri-food R&D drives productivity growth, but underinvestment in R&D persists.
- Agri-food R&D will need to address objectives beyond productivity.
- R&D investment in climate adaptation alleviates the impacts of climate change.
- Greater cross-country coordination and integration of agri-food R&D is essential.

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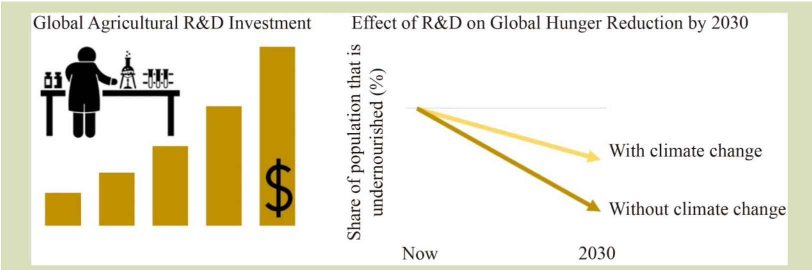
GRAPHICAL ABSTRACT



ABSTRACT

Research is essential for improvement of agricultural productivity, resource use and resilience, and for food systems transformation more broadly. This article analyzes the drivers of past agricultural productivity growth in low- and middle-income countries (LMICs) and argues that productivity is not growing fast enough to meet the needs of a global population of 10 billion by 2050. A sustainable transformation of agri-food systems in LMICs will need greater and faster technical change. Higher investment in agri-food R&D is therefore needed to accelerate productivity growth and address the social, economic, nutritional and environmental challenges facing LMICs. Greater and better-targeted investment in sustainable technologies and climate change mitigation and adaptation will be particularly important to reducing the climate change impacts on agriculture and food security in the coming decades. However, LMICs with small research systems and limited innovation capacity lack the scale and resources to effectively tackle the challenges ahead. Better coordination and a clear articulation of roles and responsibilities among national, subregional, regional and global R&D actors (both from the public and private sectors) are essential to ensuring that scarce financial, human, and infrastructure resources are optimized, duplications minimized, and synergies and complementarities enhanced.

1 INTRODUCTION: THE INNOVATION CHALLENGE

Food systems face major challenges today, and these are projected to exacerbate in the future. Shocks caused by COVID-19, the conflict in Ukraine, and their impact on income and access to food are currently at the forefront of global attention, but they come amid ongoing concerns about persistent poverty, rising inequality, malnutrition, population growth and increasing pressure on natural resources. Adding to these challenges, climate change is posing a serious threat to food security and livelihoods. Changes in temperature and precipitation, storms, floods and droughts are already making agricultural yields and prices more volatile, with rural areas around the world feeling the effects most profoundly. Yet, as global population moves toward 10 billion by 2050, unprecedented increases in food production (at least 60% above 2007 levels) will be needed to meet growing demand[1,2].

Innovation is essential to address all these challenges. It will be needed in agricultural technologies to increase and diversify agricultural production in ways that make more efficient use of resources. Innovation will also be needed in infrastructure, institutions and services that support food systems, to make them more inclusive, resilient and sustainable[3]. Some innovation will happen autonomously (e.g., as producers, consumers and other private-sector actors adjust their behavior in response to changing market and environmental conditions), but that will not be enough if sustainability, resilience and inclusivity are to be achieved. Concerted action to increase investment in agricultural research, especially in low- and middle-income countries (LMICs), will also be needed to accelerate innovation and address present and future challenges, not only in agricultural production, but also in more downstream areas such as food processing, packaging, marketing and consumption, as well as waste.

This article analyzes the crucial role of agri-food research in improving agricultural productivity, resource utilization and resilience in LMICs in the coming decades. We start by presenting a comprehensive overview of global trends in public and private agricultural research investment using updated data from International Food Policy Research Institute's Agricultural Science and Technology Indicators (ASTI) database. We then assess the impact of agricultural research investment on global agricultural productivity growth over the past 50 years and estimate the increases in agricultural research investment needed to ensure future productivity growth to feed a rapidly growing global population. In addition, we aim to contribute to an improved understanding of the political economy factors behind underinvestment in agricultural research as well as the structural characteristics of small and large LMICs that affect their capacity to innovate.

Over the coming decades, climate change will have significant impacts on the production and distribution of food[2]. Based on a review of the literature and modeling various investment scenarios, we explore how increased investments in sustainable technologies and climate change mitigation and adaptation can decrease the negative effects of climate change on agriculture and food security. Additionally, we investigate the expected outcomes of increased investment in downstream technologies in other parts of the food system beyond just agricultural production. Based on the latest available global agricultural research investment, productivity and climate change data sets, it is hoped that this article will provide significant contributions to the ongoing scientific debate on the crucial role of agri-food research and innovation in shaping the future of food systems.

2 THE SHIFTING COMPOSITION OF GLOBAL AGRICULTURAL RESEARCH

During the Green Revolution of the 1960s and 1970s, large public investment in crop genetic improvement and yield-enhancing inputs, built on the scientific advances made in high-income countries and adaptation to LMIC conditions, prompted significant yield increases, especially for maize, rice and wheat[4]. Since the 1980s, global public research investment continued to increase, doubling between 1981 and 2016 (Fig. 1), in the context of a historic transition that transformed the landscape of global food and agricultural R&D[5].

While high-income countries still accounted for the bulk of global public agricultural research spending around the year 2000, a rapid increase in spending by China and other large middle-income countries, coupled with stagnating growth in spending in high-income countries, has shifted the global balance over time (Fig. 1(a)). By 2016, LMICs accounted for nearly 60% of global public agricultural research spending. It is important to note that more than half of LMIC spending comes from just three countries: China, India, and Brazil. In contrast, the share in global public agricultural R&D spending summed across all African countries has remained stagnant over time at around 5%[5].

Adding to the shifts in global public investment, the importance of the private sector in agricultural research has rapidly increased since the 1990s. Between 1990 and 2014, global private spending on agricultural R&D tripled from about 5 to nearly 16 billion USD, indicating that private agricultural R&D spending outpaced that of public spending (Fig. 1(b)). Even though the bulk of global private R&D expenditures are made by high-income countries, more than a quarter of these expenditures by high-income countries are directly targeting commodities or research areas relevant to LMICs[7]. This rapid

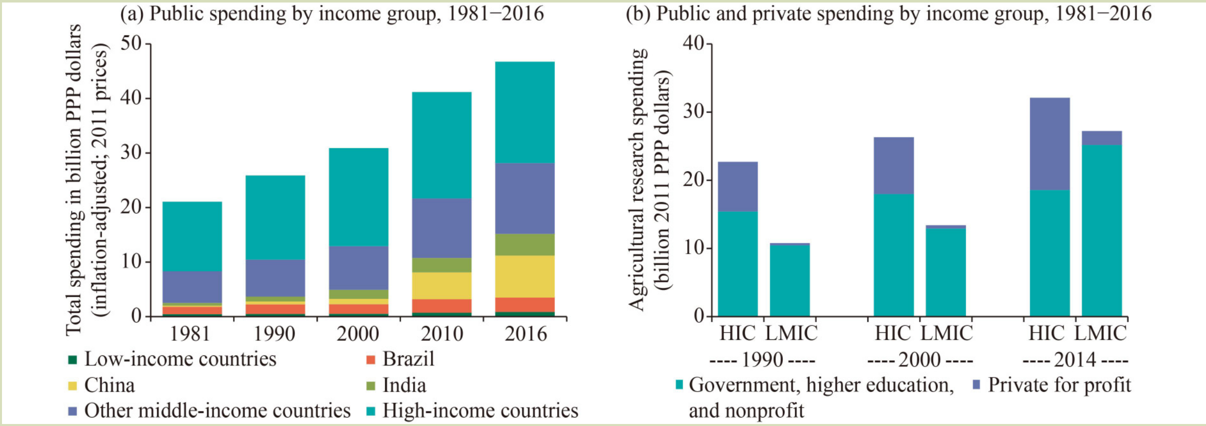


Fig. 1 Long-term trends in public (a) and public and private (b) agricultural research spending by income group. Sources: Beintema et al.[5] and Fuglie[6]. Investment levels are expressed in purchasing power parity (PPP) dollars to equalize differences in price levels across countries. Income group classifications are based on the situation in 2019. HIC = high-income countries; LMIC = low- and middle-income countries.

global increase in private investment can in part be attributed to rising commodity prices during 2002–2008, which fueled farmer willingness and ability to spend more on purchased inputs (including the latest technologies) to improve their harvests. Private companies responded by intensifying their research investment, suggesting that they expected farmer demand for productivity-enhancing technologies to continue to rise into the future[6]. Despite the importance and rapid growth of private-sector investment, it remains disproportionately focused on the commodities and issues of concern to producers and consumers in wealthier countries, leaving key gaps for agri-food systems in LMICs.

3 THE IMPORTANCE OF AGRICULTURAL PRODUCTIVITY GROWTH

LMICs have a critical need and responsibility to stimulate the growth of the agricultural sector, as growth of this sector is found to be more inclusive and to reduce poverty 2–3 times faster than growth in nonagricultural sectors[8,9]. Improvements in agricultural productivity not only raise farmer incomes, they also benefit the general population through the availability of more abundant and affordable food. Spending a lower share of income on food frees resources for non-farm goods and services, which in turn stimulates broader economic growth. Also, the accessibility of more affordable staple crops can have important nutritional benefits as well, as enabling the resources available to consumers to spent on a more diverse diet.

A significant portion of past agricultural production growth in LMICs was driven by expanding crop land (and by putting more workers to the agricultural labor force) as well as the exploitation of the natural resource base, especially in Africa (Fig. 2). However, with the main drivers of historical growth in agricultural production nearly exhausted, future agricultural growth and food security will be highly dependent on increasing the efficiency of agricultural production (i.e., more output from the same amount of resources). Total factor productivity (TFP) is an indicator of how efficiently agricultural land, labor, capital and other inputs (seed, fertilizer and the like) are used to produce a country’s agricultural outputs (crops and livestock). TFP is calculated as the ratio of total agricultural outputs to total production inputs, so when more output is produced from a constant amount of resources, TFP increases. R&D activities producing new technologies and innovations are a crucial factor driving TFP, but so there are technological spillovers from abroad, higher numbers of skilled workers, investments that favor the development of input and output markets (such as in roads and communications), and government policies and institutions that promote market development and competition. During 1996–2016, global agricultural TFP increased progressively[10].

Even though LMICs have enjoyed a substantial increase in agricultural output and productivity since the 1960s, global agricultural productivity growth (i.e., TFP) is not accelerating sufficiently to sustainably meet the needs of nearly 10 billion people by 2050. To meet the projected global demand for food through productivity growth by 2050, TFP must grow by an average rate of at least 1.75% annually[11]. However, since 2010,

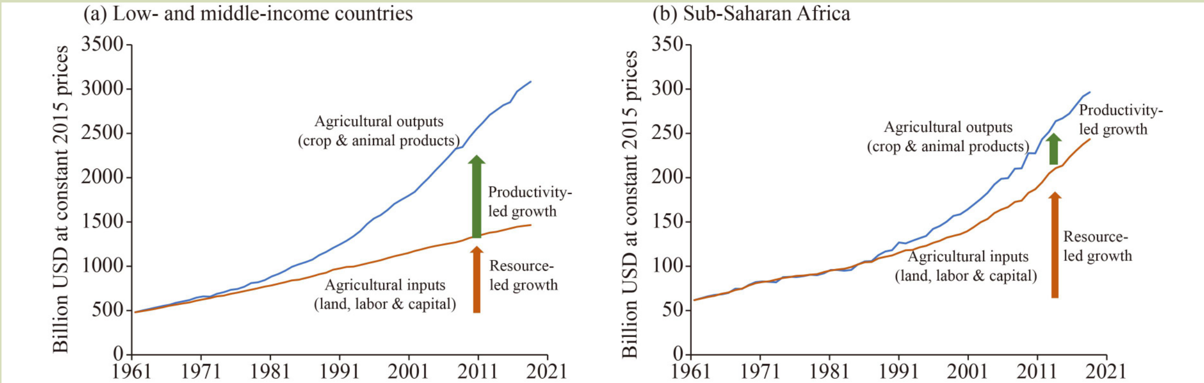


Fig. 2 Drivers of agricultural growth in LMICs (a) and sub-Saharan Africa (b), 1961–2021. Source: Calculations based on USDA-ERS international agricultural productivity database[10].

global TFP has grown at an average annual rate of just 1.51%, while annual TFP growth for low-income countries has stalled at just 0.96%. At such slow rates of growth, LMICs will only be able to meet a portion of their increased food demand through productivity improvements in the coming decades[11].

4 THE POLITICAL ECONOMY OF UNDERINVESTMENT IN AGRICULTURAL R&D

There is a vast amount of literature extending over decades showing that the returns to agricultural R&D investment average around 40%–60%[12,13]. Regardless of the mode of investments, time frame, and specific targets for adaptation chosen, studies have consistently shown that spending on agricultural research has had a greater impact on agricultural productivity than other types of public expenditures. Agricultural research spending has also performed best or second-best in reducing poverty, whether the comparison is with other investments, such as irrigation, soil conservation or farm subsidies, or with investments in other rural areas, such as health, education or roads[14,15]. A recent study by Rao et al.[16], using newly updated and expanded global data sets of estimated returns to agricultural R&D, confirms that values of reported rates of return are as high as ever finding no differences in returns between more recent and earlier investments. Nonetheless, most LMICs continue to underinvest in agricultural research.

This raises the question of why agricultural R&D investment and productivity are not accelerating if there is widespread consensus that investment in agricultural research generates high economic returns and is highly effective pathway for reducing poverty and hunger, and addressing climate change impacts of agri-food systems[17–19]. James et al.[20] highlight three main reasons for this underinvestment challenge in LMICs: incomplete markets, appropriability problems and price distortions. These issues can reduce adoption rates of new inventions, decrease the expected returns, and increase the risk of R&D investments. In addition, budget constraints and underinvestment in other public goods can result in high opportunity costs for agricultural research investment. Also, economies of scale in knowledge accumulation and dissemination may not be achievable in LMICs, and long time lags between investment and rewards can reduce political appeal and private-sector participation[20].

The returns from agricultural research investments are often widely distributed, reducing the incentives for private-sector participation. Private entities, especially smallholders, may not have the capacity to make the long-term funding commitments necessary for agricultural research. Governments therefore make a vital contribution in supporting and funding agricultural research by providing consistent funding and creating a favorable environment for innovation. However, many government decision makers face difficulties in prioritizing agricultural R&D due to its long-term nature and competition with other investment opportunities including health and education[21]. All these factors help to explain the large-scale underinvestment in agricultural research in LMICs.

5 LMICS NEED TO INCREASE PUBLIC AGRICULTURAL R&D INVESTMENT

Despite the significant barriers and disincentives for governments to invest in agricultural R&D, future agricultural productivity growth, like past growth, will remain inextricably intertwined with investments in agricultural and food R&D. Agri-food innovation systems in LMICs will continue to rely on public investment in agricultural R&D given that private-sector research investment, while significant, cannot fully close the public R&D funding gap. In the past, most of the private agricultural research investment has come from high-income countries focusing on a relatively limited number of commodities, notably cereals, soybean, horticultural crops, meat, cotton, aquaculture commodities, and oil and sugar crops[7]. This has left research on many economically and nutritionally important staple crops in LMICs (such as certain roots, tubers, legumes and important indigenous crops) relatively neglected. As such, a crucial role remains for public research agencies and international agricultural research centers, like those of the CGIAR, particularly in areas where economic incentives for private research are low.

LMICs will undoubtedly need to step up their agricultural R&D investment. However, setting one-size-fits-all investment targets for LMICs as a group is undesirable, given the vast heterogeneity among countries that compose this group. The agricultural research intensity ratio, which is obtained by dividing a country's agricultural R&D spending by a country's agricultural output (AgGDP), has been a common tool for comparing agricultural R&D expenditure levels over time and across countries, and it has been used extensively for setting R&D investment targets. The African Union, for example, recommends that countries invest at least 1% of their AgGDP in agricultural R&D. In 2016, 0.72% of global AgGDP was spent on agricultural research, but this global average masks considerable differences across regions and countries (Fig. 3). While most high-income countries as well as Brazil invest around 2%–3% of their AgGDP in agricultural research, the average intensity ratio for LMICs as a group does not exceed 0.5%[5].

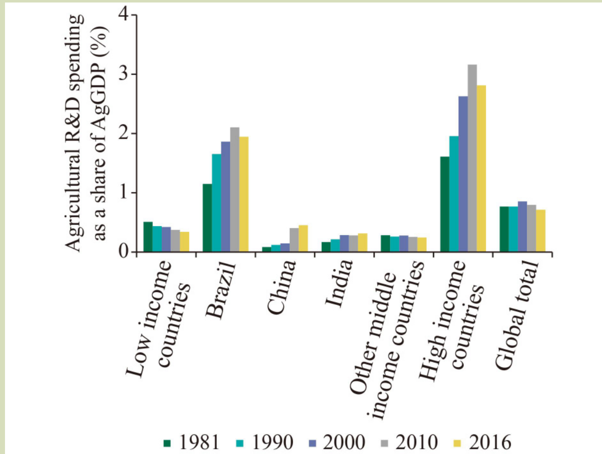


Fig. 3 Agricultural research intensity ratios by income group, 1981–2016. Source: Beintema et al.[5].

Although extensively used, agricultural research intensity ratios are based on the assumption that a country's investment in agricultural research should be proportional to the size of its agricultural sector. In reality, however, a country's capacity to invest in agricultural research depends on a range of factors, not just one. For this reason, Nin-Pratt[22] developed a more nuanced measure to estimate a country's attainable level of investment that combines the size of a country's agricultural sector with three additional variables: the size of its economy, its income level, and the availability of relevant technology spillovers from abroad. This measurement, the intensity index, is weighted according to a country's particular circumstances and comparisons with countries exhibiting similar structural characteristics. Spending below this benchmark is considered an indicator of potential underinvestment. Compared with previously used intensity ratios, the intensity index provides a considerably different perspective on the intensity of agricultural research investment, with countries like China and India recording agricultural R&D investment intensities that are quite close to attainable levels[22].

Nin-Pratt's intensity index can also be used to calculate the gap between a country's actual agricultural research investment and what is deemed attainable based on comparisons with countries of similar characteristics. This, in turn, allows the investment needed to close the R&D investment gap to be quantified. Based on this assessment, the global investment gap in agricultural research was estimated to be 34% in 2016, ranging from an average of 25% for high-income countries to 39% for both low-income and middle-income countries (Fig. 4). Underinvestment is most prevalent among countries with small and medium-sized research systems[22].

6 STRUCTURAL CHARACTERISTICS AFFECTING AGRI-FOOD INNOVATION IN LARGE AND SMALL LMICS

More problematic underinvestment in agricultural R&D in LMICs with small and medium-sized agricultural R&D systems is not surprising given the structural characteristics of the economies and agri-food systems of these countries. A recent study by Nin-Pratt and Stads[23] revealed that the level of development of a country's food system is strongly correlated

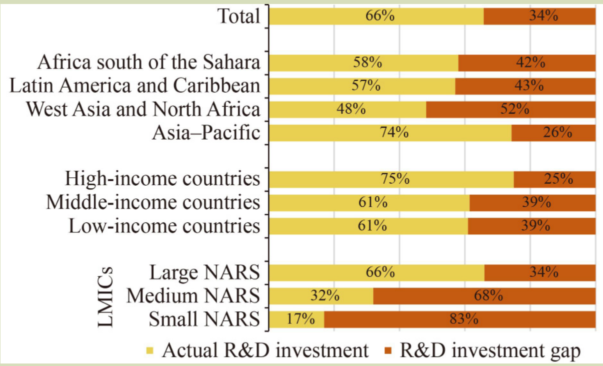


Fig. 4 Agricultural research investment gap by region, income group, and size of the national agricultural research system, 2016. Source: Calculated by authors based on Beintema et al.[5] and Nin-Pratt[22]. Data indicate the investment gap in terms of its share of actual 2016 investment. Large National Agricultural Research System (NARS) are those that fall into the upper tercile among all LMICs in terms of investment; medium NARS fall into the middle tercile; and small NARS into the bottom tercile. NARS were ranked based on their size in 2016.

to a country's research and innovation capacity. Larger LMICs like Argentina, Brazil, Chile, China, Colombia, India, Malaysia, Mexico, Pakistan, South Africa and Thailand have demonstrated a higher capacity to innovate, based on the higher quality of their education and science and technology systems, a more favorable innovation environment, as well as more developed food systems with longer and more integrated food value chains. The better innovation environment in these countries reduces risks of public investment in R&D and creates opportunities for private investment at different segments of the value chain while allowing public investment to make a more strategic contribution focusing on politically strategic subsectors or in areas where market failures persist.

In contrast, the results also showed that LMICs with small agricultural research systems, many of which are in sub-Saharan Africa, have less-developed food systems and a low capacity to innovate. The overall share of agriculture in the GDP and employment of these countries has remained relatively high, while diets remain less diversified and value chains shorter. A higher proportion of the value added by these chains is generated on farms, which use relatively low levels of capital inputs and demonstrate lower levels of land and labor productivity compared to farms in countries with more developed food systems. Low enrollment and quality of the education system are constraining the supply of researchers, while low levels of local competition, poor and expensive services, and restricted access to credit are additional factors holding back these countries with less-developed food systems in their capacity to innovate. Adding to this, the scarce resources of research systems in smaller LMICs are spread thinly over a wide range of demands increasing the inherent risks of agricultural research and the quality of the final research outputs. The cost of research per unit of output is estimated to be nearly four times lower in HICs than in LMICs with small agricultural R&D systems, pointing to important inefficiencies in the latter group[23].

These findings suggest that closing the agricultural R&D investment gap, discussed above, will depend on faster and sustained growth in larger LMICs. Countries with both small research systems and low potential to increase their investment in agricultural research would need to adopt alternative strategies, such as, collaboration with countries and regions that share mutual research needs and goals, to acquire the knowledge and technologies they need to achieve agricultural development and growth in the coming decades.

7 AGRI-FOOD R&D NEEDS TO ADDRESS OBJECTIVES BEYOND PRODUCTIVITY GROWTH

Even though productivity growth must continue to be a priority to sustainably meet food demand in LMICs, higher productivity alone is not sufficient to achieve economically, environmentally and socially sustainable, and inclusive agri-food systems. Food systems are major drivers of changes in land use, depletion of freshwater resources, and pollution of aquatic and terrestrial ecosystems, and the production of food (especially animal-source foods) generates more than a third of the anthropogenic greenhouse gas (GHG) emissions that cause climate change. Contributing to these pressures, climate change will be a major determinant of the quality and quantity of food produced, and of the ability to distribute it equitably in the coming decades[2,24–26]. However, only 7% of LMIC spending on agricultural innovation is currently estimated to be targeting sustainable agricultural intensification investments, showing only little change over time[27]. Therefore, increased investment will need to be directed to research and innovation focused on healthier and more sustainable diets, improvements in technology and management, reductions in food waste and loss, mitigation of GHG emissions, and increased smallholder resilience and adaptation to climate change[28].

Increased R&D investment in both sustainable technology (including land productivity restoration) and climate change mitigation and adaptation will be key to reducing, if not offsetting, climate change impacts on agriculture and food security. A recent study by Baldos et al.[29] showed that the returns to R&D-led adaptation in developing regions ranged from 3.7 to 5.2 times the amount invested, although these estimates are sensitive to the values of the R&D elasticities, a measure of the future productivity of agricultural research in the face of climate change. With low research productivity, the expected adaptation costs are 2 to 3 times higher than the baseline estimate and could result in negative returns to R&D investment.

In contrast, R&D investments in climate adaptation help to alleviate the impacts of climate change on productivity and market access (and thus indirectly on food prices, cropland expansion and consequent GHG emissions). These co-benefits provide further justification for R&D investments targeting climate adaptation and mitigation. For example, higher food prices resulting from the impact on crop yield from climate change would adversely affect the world's poor, particularly small-scale farming families that consume more than they produce. The economic response of farming communities to these higher prices would be to use more inputs, especially land. This will lead to additional releases of GHG emissions into the atmosphere due to intensification and cropland expansion. The avoidable increase in cropland use and subsequent GHG emissions that could result from increasing research on adaptation to climate change has been estimated to range from 11 to 53 Mha and 31 to 153 Mt CO_2 equivalents, respectively, depending on the expected impact of climate change on yields[29]. Successful adaptation could also lower the number of undernourished people by 24 million to 90 million, with averted produce price increase ranging from 4% to 23%[29].

The performance of technological advances will vary across the diverse contexts in which these advances are applied[30]. A clear example is that drought-tolerant varieties provide greater benefits to farmers and consumers under climate futures with strong decreases in growing season rainfall. Likewise, improved nitrogen use efficiency is only useful in cropping systems where nitrogen availability is a constraining factor for productivity. Climate change tends to make agricultural R&D and complementary investments less impactful in percentage terms, but more so in absolute terms (Fig. 5)[2]. There can also be overlapping factors that drive the importance of different elements of the production system up or down. Labor-saving technologies can be of great benefit on small-scale farms, but if soils are nutrient-poor, productivity might not increase commensurate with the saving in labor. Investments and innovations need to be tailored to the specific context in which they are being applied[8].

There is also a nonlinear relationship between climate change impacts and the effectiveness of increased R&D investments or particular innovations. Changes in trends for average temperature and precipitation are drivers that can mostly be addressed through normal adaptation processes in the food system. The impacts of expected changes in income and population, and therefore per capita incomes, are projected to outweigh the impacts of average changes in climate trends though to the middle of this century[26], but extreme and unanticipated shocks will present greater challenges. The impact of climate change will depend on the resilience of communities, with more affluent societies being capable of enduring shocks and recovering quickly. Likewise, the effectiveness of different interventions will interact with different levels of socioeconomic status, the severity of climate change, and other factors.

As most research on adaptation to climate change has focused on agricultural production, climate change has other implications for the food system that remain largely unexplored. Potential impacts of climate change on food systems include the effects of extreme events and sea level rise on agriculture-related services, transportation infrastructure, changes in the design and location of storage facilities, the effects of regulatory policies on the adaptive capacity of the food system, and the implications of energy and GHG mitigation policies for the economics of domestic food systems[31]. For example, Reardon et al.[32] argue that research on processing, packaging, logistics, and commerce technologies have equal weight in the performance of the food system relative to the farm sector. In addition, returns on research at the farm level depend on innovations in the supply chain that help determine whether innovations in agricultural technology will lead to increased marketability and profitability of farm outputs and hence the adoption of these innovations by farmers. R&D investment for downstream technologies in the food system will need a much higher profile in the context of climate change and the development of food systems.

8 CONCLUSIONS AND PRIORITIES FOR ACTION

Agri-food systems around the globe need to provide sufficient and nutritious food. At the same time, they need to enable producers to earn a decent living, while minimizing environmental harm, and adapting and responding to climate

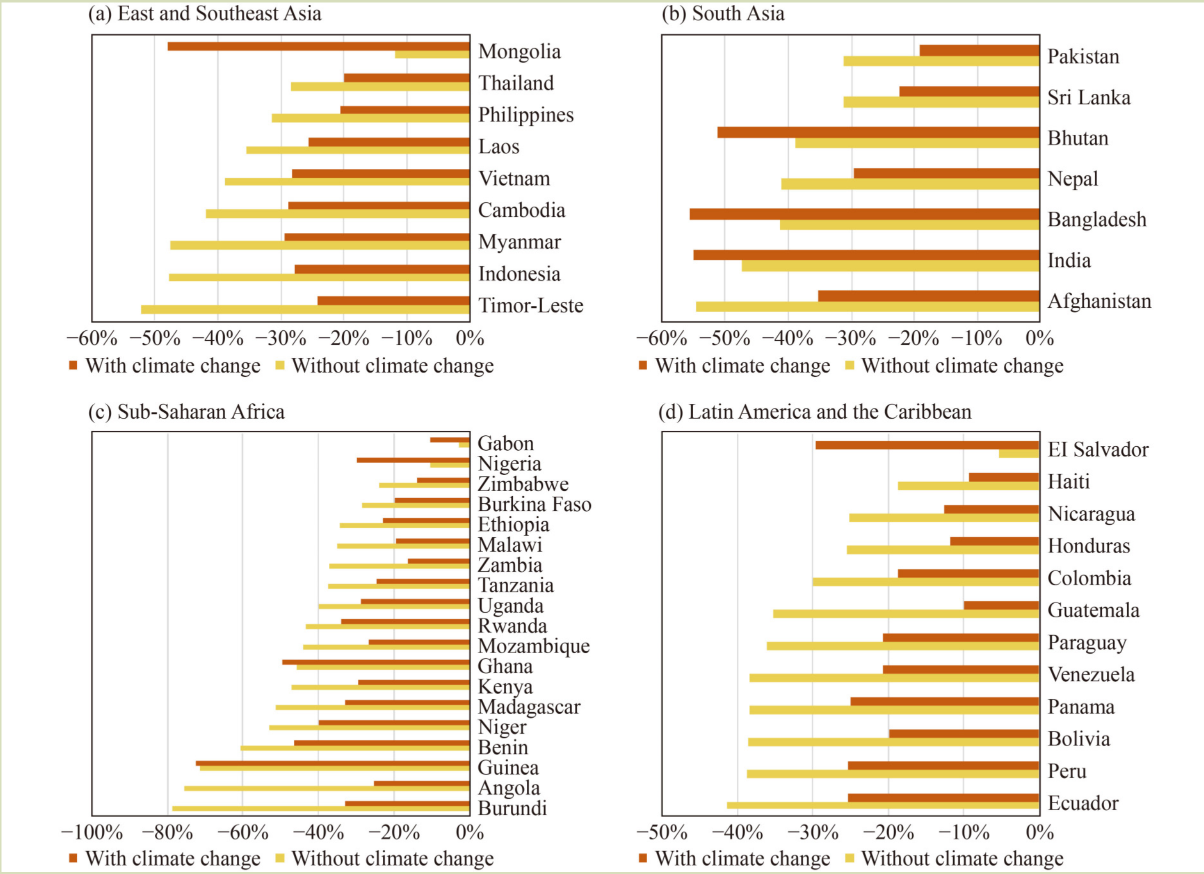


Fig. 5 Impact of investments in agricultural R&D, water management and market access infrastructure on hunger reduction with and without climate change (percent reduction in 2030 compared to reference scenario in the same year) for selected countries in East and Southeast Asia (a), South Asia (b), sub-Saharan Africa (c), and Latin America and the Caribbean (d). Source: Data for selected countries from Sulser et al.[2]. Scenarios assume middle-of-the-road changes in population and income, based on the Intergovernmental Panel on Climate Change's (IPCC's) shared socioeconomic pathway (SSP) 2. Climate change is modeled based on IPCC's Representative Concentration Pathway (RCP) 8.5 scenario. See Sulser et al.[2] for details.

change and other global challenges. Over the past decades, agricultural productivity has not been growing fast enough to meet the needs of a global population that will be approaching 10 billion by 2050. Greater and faster technical change is needed in the decades ahead for a sustainable transformation of agri-food systems. This requires higher investment in agri-food R&D to accelerate productivity growth and address the social, economic, nutritional and environmental challenges faced by LMICs. Greater and better-targeted investment in sustainable technologies and climate change mitigation and adaptation will be particularly important to reducing the climate change impacts on agriculture and food security in the coming decades.

Despite widespread evidence of high rates of return on agricultural R&D investment, there is widespread underinvestment in agricultural R&D in LMICs. Collectively, LMICs invest less than 0.5% of their agricultural GDP in agricultural R&D, and even though R&D investment represents only a small portion of total investments in agri-food innovation, the low value of this indicator points to problematic levels of underinvestment nonetheless. von Braun et al.[33] recommend that countries allocate at least 1% of their food-system-related GDP to food systems research. Detailed information on global investment in food research is not available, but the agricultural R&D expenditure data for LMICs presented in this article suggest that such an ambitious investment target will require substantial effort.

Agricultural R&D investment will undoubtedly need to increase, but a universal investment target may not be appropriate for all LMICs, as they face diverse challenges.

Smaller LMICs have limited innovation capacity and economies of scale, making it difficult for their scarce R&D resources to efficiently tackle priorities for multiple commodities and agroecological zones. In contrast, larger LMICs like China, India, and Brazil have advanced R&D systems producing world-class innovations. Economies of scale have allowed these nations to experience substantial growth in knowledge accumulation and dissemination over time. In fact, these countries have been the main drivers of global growth in agricultural R&D investment since the year 2000.

To improve the productivity and efficiency of agricultural R&D in all LMICs, both large and small, it is crucial to make the most of available resources and minimize the downsides of small operations. To achieve this, action is needed on the following priorities.

(1) Agricultural R&D and innovation need to be integrated and better coordinated at the (sub-)regional level to minimize duplication and maximize synergies, complementarities and cost-effectiveness. Smaller countries will need to align their research efforts more closely with countries with large research systems that share mutual research needs and goals to enhance shared benefits. Continued support for and growth of regional bodies, networks and mechanisms will further aid in defining, implementing and funding agendas that target issues of (sub-)regional interest. This coordination and integration process will require clear definition of roles and responsibilities among national, subregional, regional and global R&D actors and important institutional reform.

(2) Research efficiency needs to be enhanced by defining priorities more strategically, reducing research scope, focusing on solutions rather than commodities or themes, and adjusting research organizations and governance to these changes. When setting research and innovation priorities, countries and regions should aim for sustainability, inclusiveness, and scalability, and evaluate where additional spending will have the biggest impact on productivity growth and climate change adaptation and mitigation. Investments should target innovations not only in primary production, but also in post-harvest handling, storage, processing, distribution and consumption of food and agricultural commodities. These national and regional innovation investments must be coordinated with broader public and private investments, such as in infrastructure, financial services and technology, for seamless integration into the food system.

(3) Private-sector investment in food innovation needs to be encouraged, particularly in the post-harvest stages of value chains. Encouraging private funding requires that national governments provide a more enabling policy environment through tax incentives, protection of intellectual property rights and regulatory reforms to encourage the inward flows of international technology. Countries also need to forge and leverage new mechanisms and partnerships that bring together different investors and stakeholders, including small-scale farmers.

Compliance with ethics guidelines

Gert-Jan Stads, Alejandro Nin-Pratt, Keith Wiebe, Timothy B. Sulser, and Rui Benfica declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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