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Innovation in Food Systems: Challenges and Opportunities

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Introduction

Agricultural innovation has played a major role in improving food security, reducing hunger and poverty, and improving rural livelihoods. Agricultural innovations such as improved seed varieties have enabled smallholder farmers to increase their yields and incomes. Innovation in agribusiness has created new employment opportunities and improved access to markets for farmers, leading to increased incomes and better livelihoods (Pingali 2012). But agricultural growth has been accompanied by negative effects on climate, natural environment, public health and nutrition, and social justice (Barrett et al. 2020a; Pingali 2012). Therefore, an innovation paradigm shift is necessary, where productivity growth remains essential, but other critical objectives such as poverty reduction, promotion of healthy diets, mitigation of the climate and biodiversity and extinction crises, and building resilience must also be accommodated (Barrett et al. 2020a).

Achieving such a transformation will require huge investment in innovations for sustainable agriculture intensification. These innovations should aim to produce the food necessary to meet changing human nutrition needs while also ensuring the long-term productive potential of natural resources, such as water and land resources, and their associated ecosystems and functions.

As noted by van der Veen (2010), until recent years agricultural innovations were primarily concerned with the need to increase production of food, fodder, and secondary products as well as enhancing quality of produce, production process, and growing conditions. Innovations were seen to have an impact on at least one of these five areas: crops, animals, cultivation conditions, tools, and management methods. But the definition of agricultural innovation has broadened with the adoption of a food systems approach. FAO (2019) defines agricultural innovation as "processes whereby individuals or organizations bring new or existing products, processes, or ways of organization into use for the first time in a specific context in order to increase effectiveness, competitiveness, resilience to shocks or environmental sustainability and thereby contribute to food security and nutrition, economic development or sustainable natural resource management" (FAO 2019). Innovation includes changes in practices, norms, markets, and institutional arrangements, which may foster new networks of food production, processing, distribution, and consumption that may disrupt the existing system (HLPE 2019).

This note discusses keys aspects of agricultural innovation systems including the magnitude and allocation of expenditures on agricultural innovation and how innovation priorities are determined. Then we discuss areas where the innovation system could be strengthened, including modernization of plant and livestock breeding; seeking more sustainable farming systems; the development of digital agriculture; enhancement of value chains; and scaling up of innovations.

Expenditures on agricultural innovation

In this section we summarize the available information for expenditures on agricultural innovation in total for the Global South and for CGIAR and for NARS. The Global South total includes traditional public and private

R&D, marketing of technical innovations, funding of innovations to create or enhance institutions or infrastructure, and funding for new policies and subsidies to encourage innovation adoption. The next two sections focus on public expenditures specifically on agricultural research and development, first by CGIAR, and next by the NARS. CGIAR is funded mainly by "development partners" (including multilateral development banks, bilateral aid agencies, and philanthropic foundations). Bilateral aid agencies are by far the biggest donors to CGIAR. As you note, expenditures by the NARS come from national budgets in low- and middle-income countries (LMICs). Finally, private sector agricultural research and development expenditures in LMICs are summarized.

Although not all investments in agricultural research and development are successful, overall these investments have very high rates of return (Alston 2000; Pardey, Andrade, et al. 2016; Pardey, Chan-Kang, et al. 2016). In a recent study, Alston, Pardey, and Rao (2020) assessed a sample of 780 observations of benefit cost ratios (BCR) estimates, including 203 BCRs for CGIAR R&D and 577 BCR estimates for non-CGIAR (public, developing country) R&D such as national agricultural research systems (NARS). The median estimated BCRs for both CGIAR research and developing-country NARS research are about 10:1. BCRs of 10:1 are very high compared to other public investments.

Total agricultural innovation expenditures funding in low- and- middle-income countries

Prasad et al. (2023) assesses total expenditures on agricultural innovation by four key categories of funders for agricultural innovation globally: 1) Global South governments (domestic budgets); 2) development partners (bilateral, multilateral, and philanthropic donors); 3) private companies; and 4) private equity and venture capital (PE/VC) investors. The term "Global South" used in Prasad et al. (2023) follows the World Bank classification of low- and- middle-income countries. This study includes all funding related to the creation or adoption of new agricultural technologies, practices, and systems. In addition to purely technological innovation, the study includes funding in non-technological areas such as business models, policy reforms, agricultural extension and training, process innovations, and marketing funding on innovative technologies. All values were converted to constant 2019 prices and constant 2019 US$ exchange rate (Prasad et al. 2023).[i]

According to the broad definition used in this study, the estimated average total annual funding for agricultural research and innovation in the Global South between 2010 and 2019 was around $60 billion per year (with a range of $50-70 billion). Traditional public and private R&D, which involves scientific research and development of new technical products and services, accounted for 33% of the total innovation funding. Another 37% was dedicated to the marketing of technical innovations, along with extension services and training programs provided by both public and private sectors to assist farmers and producers in adopting these innovations. Around 26% of the funding was directed towards innovations that aimed to create or enhance institutions or infrastructure. The funding for new policies and subsidies to encourage innovation adoption represented less than 5% of the overall spending (Prasad et al. 2023).

Between 2010 and 2019, Global South governments were responsible for approximately 60-70% of the total innovation funding, with the private sector contributing 15-30%, development partners (including multilateral development banks, bilateral aid agencies, and philanthropic foundations) accounting for about 8%, and startups funded by PE/VC representing 2-3% of the total funding. Over the course of the decade, funding for innovation in food commodity value chains increased by roughly 50% (both in real terms and as a percentage). Within value chain-related funding, crops received 50-60% of the funding, while livestock received less than 20%, and fisheries and aquaculture received approximately 5%. The remaining 20% of funding was dedicated to cross-cutting themes such as forest preservation, water conservation, and general agricultural reforms.

CGIAR expenditures

CGIAR spending has shown an upward trend over time, although it has been marked by periods of fluctuations. In 2014, total CGIAR spending in constant 2016 US dollar values reached its peak at $1,089 million, but it subsequently declined to $824 million in 2018 (Alston, Pardey, and Rao 2020). CGIAR represents a relatively small portion of global spending on agricultural R&D. When it was first established in 1971, CGIAR represented only 0.52% of the world's public-sector spending on agricultural R&D. By 2015, the latest year for which comparative non-CGIAR research spending data are available, this figure had increased to 2.1%. However, CGIAR accounts for a larger and similarly increasing share of publicly performed agricultural R&D in developing countries, increasing from 1.2% in 1971 to 4.2% in 2015 (Alston, Pardey, and Rao 2020).

Changes in CGIAR's structure and accounting norms complicate the compilation of research spending data that consistently reflects the programmatic orientation of their activities. Pardey and Chan-Kang's (2020) analysis of CGIAR's annual financial reports provides evidence on research focus. On average from 1972-2005, 45% of funding went towards "productivity," 21% to "NARS strengthening," 8% to "biodiversity," 15% to "environment," and 11% to "policy-related activities." (Alston, Pardey, and Rao 2020). Over time, CGIAR's activities shifted considerably. In the early 1970s, almost 75% of spending focused on improving (crop) productivity, but by the early 2000s, this decreased to under 33%. Meanwhile, there was an increasing emphasis on biodiversity conservation (2.4% to 11.4%), environmental activities (9.1% to 17%), and policy-related efforts (1.1% to 16.3%). NARS-strengthening remained relatively consistent (17.2% to 21%) (Pardey and Chan-Kang 2020, summarized in Alston, Pardey, and Rao 2020).

Over time, CGIAR reduced spending on cereals (56% to 33%) while investments in livestock dropped from 20% in the 1980s to 12% in the early 2000s and legumes fell from 18% to 11%. The second expansion of centers, starting in the 1990s, brought new centers focusing on trees, bananas/plantains, and water, resulting in increased spending on these areas. However, changes in reporting and institutional structures in 2011 make it difficult to compare more recent commodity shares with earlier ones (Pardey and Chan-Kang 2020, summarized in Alston, Pardey, and Rao 2020).

Even with this reduced spending on staple crops, Haddad (2020) argues that the CGIAR's—and NARS's—focus on staple crops such as wheat, maize, and rice should be balanced with increased attention to foods such as vegetables, fruits, fish, pulses, nuts, eggs, dairy, and meat). These commodities are excellent sources of micronutrients, and plant-based commodities also reduce the likelihood of diet-related chronic disease (Haddad 2020). And Pingali (2015) stated that agricultural policy was still deeply biased towards staple grain productivity growth, particularly for the big three cereal crops – rice, wheat and maize–without adequately tackling the diet diversity needs of the poor and middle class.

But CGIAR R&D expenditure allocations have evolved substantially since the early 2000's. Based on expenditures for the 2021 CGIAR Research Programs, staple crops (rice, wheat, maize) accounted for 21% of expenditure and non-staple crops (roots, tubers, bananas, grain legumes, and dryland cereals) account for 17%. Resource management (forests, trees, and agroforestry; and water, land, and ecosystems) accounted for 15%, fish and livestock accounted for 11%, climate change for 10%, agriculture nutrition and health for 10%, policy for 7%, and cross cutting platforms (gene bank, excellence in breeding, gender, big data) for 9% (computed from CGIAR 2023).

This expenditure portfolio is considerably more balanced than previously and further cuts in staple foods research and development may be ill-advised. The number of people affected by hunger globally (estimated based on dietary energy) rose to 828 million in 2021, an increase of about 46 million since 2020. The proportion of people affected by hunger is also increasing, to 9.8% of the world population, compared to 8% in 2019 and 9.3% in 2020 (FAO, IFAD, UNICEF, WFP and WHO, 2022). Fuglie et al. (2022) find that productivity increases in grains generate the largest reduction in the number of people affected by population at risk of hunger compared to other crops, as well as the largest increase in per capita nutrient availability for protein, zinc, and iron.

Functionally, the bulk of funding for crop breeding should go to boosting yields and production efficiency, since increasing efficiency also contributes to reduced area expansion, less deforestation, water use, and GHG emissions. As Lobell (2020) notes, "CGIAR can play a key role in slowing climate change by raising agricultural productivity fast enough to avoid additional pressure to convert new lands into agriculture." Crop productivity growth can play a key role with respect to climate change without over reliance on breeding for specific traits such as drought tolerance or sequestering carbon in soils.

However, there should be a shift on the margin to breeding for traits that directly address climate-related crop breeding and improved nutrition content. Traits to address climate change include drought and heat and drought tolerance and resistance to pests and disease that will be more severe in hotter and wetter conditions. Breeding of biofortified crops, such as orange-fleshed sweet potatoes, can reach malnourished rural populations who generally have limited access to diverse diets, supplements, and commercially fortified foods (Haddad 2020). Likewise, R&D programs for livestock should focus not only on efficiency and productivity, but also on product quality, disease resistance, reductions in GHG emissions and water saving from improved management. and mitigating other environmental impacts (Thornton 2010).

But CGIAR does not have a mandate in vegetables and fruits. These commodities are better handled through partnerships that include better understanding of the value chain and other off-farm activities and the impact of policies. An assessment by Anderson and Birner (2022) suggest that genetic improvement for fruits and vegetables may be more effectively pursued by the private sector, while CGIAR and other international agricultural programs could prioritize the development of strategies for integrated pest management, biological pest control, and improved water use efficiency, areas where private companies have limited financial incentives. Additionally, publicly funded research could contribute to the discovery of cost-effective solutions in the value chain to improve the effectiveness for small farmers.

Finally, crop and livestock breeding should not be relied upon to solve problems that go beyond the core breeding goals discussed here. Other aspects of agricultural development such as poverty reduction, livelihoods, environmental sustainability, as well as most nutrition goals, are best addressed by economic, ecological, and social policy. CGIAR research programs on resource management, agriculture health and nutrition, climate change, and policy—and their successors—recognize this reality.

Beintema and Echeverria (2020) identify additional important trends in CGIAR funding. Donor commitment has remained stable over time. However, the organization has not attracted many significant new donors, with the big exception of the Bill & Melinda Gates Foundation, which is now the third biggest donor to CGIAR. CGIAR aims to achieve long-term international research outcomes and impacts, particularly in areas such as breeding. However, the prevalence of funding for short-term projects instead of longer-term institutional research programs is concerning. This emphasis on short-term projects risks undermining the continuity of research and may limit the CGIAR's capacity to deliver long-term impact. It is essential to strike a balance between short-term projects and longer-term institutional research programs to achieve CGIAR's mission effectively (Beintema and Echeverria 2020).

NARS funding

Following a decade of slow growth in the 1990s, global agricultural research spending (excluding the private for-profit sector) in LMICs rose from $13 to $28 billion during 2000–2016, measured in inflation-adjusted, purchasing power parity (PPP) dollars (Beintema, Nin Pratt, and Gert-Stads (2020).[ii] China accounted for 44%

of the growth during this period. Three countries dominated NARS research expenditures in 2016: China ($8 billion), India at $4 billion, and Brazil at $3 billion. By contrast, the whole sub-Saharan Africa spent only $2.3 billion. Analysis of low- and middle-income countries show that underinvestment is prevalent among countries with small and medium-sized research systems. Given these low levels of expenditures, to achieve improved agricultural development and growth in the coming decades, countries with small research systems and insufficient potential to increase their investment in agricultural research need to explore alternative strategies. Collaborating with countries and regions that share mutual research needs and goals can provide them with the necessary knowledge and technologies (Beintema, Nin Pratt, and Gert-Stads 2020).

The Role of Private Investment

Private agricultural R&D in developing countries has been a relatively small share of agricultural R&D in developing countries (Fuglie 2016). Private sector spending amounted to less than 10% of public sector expenditures in developing countries in 2014. Private research is concentrated on a relatively small number of commodities. According to Fuglie (2016), the private sector invests mainly in commercially important commodities, mostly maize and soybeans, followed by fruit and vegetables, wheat, poultry, rice, pigs, cotton, oilseed, sugar crops, and aquaculture. However, crops like cassava, yams, sweet potatoes, coffee, and cocoa, which are economically significant in many low- and middle-income countries, particularly in Africa, receive inadequate investment from the private sector. Therefore, NARS, universities, commodity boards, and CGIAR centers still have a dominant role to play, particularly in areas where incentives for private research are low (Beintema, Nin Pratt, and Gert-Stads 2020).

Priority Setting

Public research systems face a myriad of goals and priorities, some of them requiring tradeoffs. CGIAR, for example, has set broad strategic goals: (1) nutrition, health, and food security; (2) poverty reduction, livelihoods, and jobs; (3) gender equality, youth, and inclusion; (4) climate adaptation and mitigation; and (5) environmental health and biodiversity (CGIAR 2020). Choosing priorities across such a wide range of goals is a daunting task. Private sector breeders develop a product profile of the variety that farmers would prefer relative to those they are already growing and then use this to define the breeding objectives (Cobb et al. 2019). A product profile is a set of targeted attributes that a new plant variety should have to be successfully adopted by farmers. A product profile usually focuses breeding efforts on the key traits that drive farmer income (Cobb et al. 2019 cited in Kholová et al. 2021). CGIAR and NARS must also consider the social, economic, and environmental impact of their research priorities, particularly on marginalized and vulnerable groups, such as smallholder farmers, women, and youth. Research on crop varieties or farming techniques that are accessible and affordable to these groups can enhance their livelihoods and reduce poverty. Priority setting is much more complex with these multiple goals.

Various approaches are used for priority setting to tackle these complexities. These approaches can be broadly grouped as participatory approach, expert-based, and data-driven. The participatory approach involves stakeholders, such as farmers, researchers, policymakers, and civil society organizations, in the priority-setting process. This approach is useful because it ensures that the needs and concerns of all stakeholders are considered, and the priorities are aligned with the needs of the community.

Technical innovations have more often been "pushed" from R&D and effective marketing of new discoveries, rather than being "pulled" by farmers and consumers demanding new ways of doing things. The siloed organization of innovation and governance systems often leads to the creation of new products and practices, focused solely on narrow commercial, political, or scientific aims, without assessing synergies and tradeoffs more broadly (Barrett et al. 2020b). In the past it has been difficult to generate and aggregate pull factors from farmers and consumers since they represent a widely dispersed market with limited information available. But advances in information technology and networking systems have led to wider adoption of participatory approaches in priority setting and implementation of innovations.

To address the limitations of the push approach, there has been a growing emphasis on developing multi-stakeholder innovation platforms and networks. HLPE (2019) summarizes important shifts towards a more participatory approach in international agricultural research, which include facilitating farmer networking (Nelson et al. 2016); utilizing citizen science and ICT to gather and share information from many farmers (van Etten et al. 2019; Dehnen-Schmutz et al. 2016); and embedding research in development initiatives through planned comparisons (Coe et al. 2014). These approaches promote farmer participation, but it is essential the farmers have sufficient control over data and the design choices and feedback mechanisms (Sinclair and Coe 2019). Participatory varietal selection and plant breeding have successfully utilized farmer participation for several decades (Tiwari et al. 2009).

A common feature of these approaches is that they use multistakeholder innovation platforms (Schut et al. 2018). Multi-stakeholder innovation platforms are important because they generate innovations that can support transitions and have a significant impact at-scale. By involving multiple stakeholders, these platforms can ensure that a diverse range of perspectives and expertise is included, leading to more holistic and effective solutions.

The expert-based approach involves experts in agriculture, science, and technology in the priority-setting process. This approach can be useful when there is a need for a quick decision, and there is limited time to involve stakeholders, but it is better used in conjunction with other priority setting techniques. The data-driven approach uses data analysis to identify the most critical areas for research. This approach is useful when there is a large amount of data available.

The data-driven approach with elements of expert opinion is exemplified by the 2012-2014 priority-setting exercise by the CGIAR Research Program on Roots, Tubers, and Bananas (RTB) (Pemsl, et al. 2022). RTB conducted a systematic, quantitative, ex-ante assessment of cassava, banana, potato, sweet potato, to inform research portfolio decisions. Studies were conducted using a harmonized framework, including: 1) surveys of production constraints and research opportunities via global experts, 2) identification of priority research interventions, 3) estimation of costs and benefits for two adoption scenarios, and 4) poverty impact simulations. Results showed substantial but variable benefits for all potential research investments, with impact indicators such as adoption area, beneficiaries, net present value, internal rate of return, and poverty reduction. The findings informed RTB's research portfolio development and were critical for securing program funding in phase two (Pemsl, et al. 2022).

NARS priorities are also often influenced by political priorities and power dynamics in a country. Political leaders and producer groups may have different agendas and preferences for research priorities, which may not necessarily align with scientific or stakeholder needs, and financial resources and economic expertise for priority setting are often limited (Pemsl, et al. 2020). CGIAR also faces pressure from donors and in the countries in which they are working.

Modernization of Breeding

Crop breeding programs in LMICs should be implemented in close partnership among CGIAR, NARS, universities worldwide, farmer-led breeding initiatives, and the private sector where appropriate. A greater push should be made both within CGIAR and through capacity building for NARS in low-income countries to increase research efficiency through development an application of modern data collection, digitalization, and information management systems that can revolutionize breeding. These include high-throughput phenotyping, GIS, genomic-wide association selection, meteorology, and soil characterization as well as monitoring of farm management practices, including the performance of cultivars. These innovations require institutional reforms to implement modern information platforms based on data management and decision-support software that integrate information and apply sophisticated analytical workflows to information (Kholová et al. 2021).

NARS play an especially important role in partnership with CGIAR, identifying key targets for breeding programs, generating their own improved germplasm, adapting CGIAR-generated germplasm to local conditions, and facilitating links with farmers. A more functional partnership model will mean NARS take greater ownership of germplasm and greater responsibility for downstream parts of the breeding pipeline, as well as managerial roles. Stronger partnerships mean more ownership and capacity to rapidly deploy improved crop varieties and drive variety.

CGIAR's new Accelerated Breeding Initiative is seeking to achieve this modernization of breeding and improved partnerships to streamline breeding across CGIAR and NARS to bring better results, faster, in farmers' fields, to deliver higher rates of genetic gain with nutritious, farmer-preferred varieties (CGIAR 2022). ABI will refocus breeding programs to prioritize meeting farmers' needs by developing and adapting product profiles that are targeted to farmers and customers, including women, based on market intelligence. In addition to this, the ABI aims to transform breeding networks into inclusive, impactful partnerships with stronger NARS and small and medium enterprise partners. This requires tailored capacity building, and division of labor and resources across partners according to comparative advantage.

To expedite the delivery of novel and valuable traits to breeding teams, investment in trait discovery and deployment activities will be sharpened. This investment aims to better respond to the specific trait needs of core breeding pipelines and the markets they serve, ensuring greater speed and accuracy in trait delivery. Ultimately, the ABI intends to modernize breeding programs to efficiently deliver better targeted and market-demanded varieties that result benefit farmers, increase productivity, and support food security (CGIAR 2022).

Sustainable Cropping Systems

Another major focus for innovation should be the development of scaled-up farming systems that boost farm-level efficiency, production, and income and as a result also become more environmentally friendly and climate smart. Such technologies include the use of crop rotations 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.

Innovative farming systems can generate high returns, but improved farm technologies and systems are more complex and difficult to adopt than seeds for improved crop varieties. In most cases the benefits to farmers are not as visible and it can take years to achieve net income benefits relative to the costs of adoption. For example, implementing integrated soil and water management immediately increases costs, but yield gains can take years to realize as soil quality only improves over time (Rosegrant et al. 2015).

Despite this, in many food-insecure regions, potential productivity gains from improved management are often far greater than from improved genetics. But effective management depends a lot on local soil, weather, plot history, and economic conditions, and many “best practice” recommendations do not generate profits for a large fraction of farmers (Jayne et al. 2018). However, new precision agronomy technologies can help to diagnose the major needs more quickly at subnational and field scales assisting to identify crop management and technologies and improve the design of farming systems suited for local agroclimatic conditions that offer greater diversification of opportunities (Lobell, 2020).

Current policies have hindered the adoption of climate-smart and resource-saving technologies and diversified cropping by small-scale farmers. Correcting government policies that discourage the adoption and upscaling of innovations is crucial. For instance, price support for rice, wheat, and maize promotes these crops' profitability at the expense of other crops, discouraging the planting and production of nutrient-rich and other diversified crops. Additionally, subsidies for fertilizer, water, energy, and pesticides lead to the overuse of these inputs, causing excessive GHG emissions and environmental degradation (Rosegrant 2019). These costly general subsidies should be phased out and the budgetary savings from the reduction of subsidies invested in agricultural R&D, non-distorting income support for small farmers, or social protection.

Policy innovations are needed, integrated with farming systems innovation to facilitate the effective adoption of such new technologies with balanced incentives that do not disadvantage small farmers. Carbon payments and other targeted smart subsidies have the potential to incentivize specific goals, such as carbon mitigation and the promotion of environmental services. Subsidies may include loans or targeted equipment prices for practices like drip irrigation and labor and installation costs for small-scale solar pumps. Temporary subsidies can overcome adoption fixed costs of adoption, reduce risk, and promote farmer experimentation during adoption (Rosegrant et al. 2021). These subsidies should phase out as adoption becomes more widespread. Implementation requires caution to avoid political support for entrenched subsidies (Goyal and Nash 2017; Rosegrant 2019).

The policies to sustain intensified agriculture while protecting the environment need to create a level playing field across the agriculture sector (Pingali 2015). In the broadest sense, these are policies to improve the flexibility of resource allocation in agriculture – through the removal of incentive-distorting subsidies and taxes; the establishment of secure property rights; increased investments in research, education, and training; improved public infrastructure; better integration of international commodity markets; and a greater inclusion of populations in developing countries into these markets. (Pingali and Rosegrant 2000)

Digital Agriculture

A key priority for farming systems management should be development of advanced digital technologies–such as satellite imaging, remote sensing, and in-field sensors–which can support precision farming based on observations of, and responses to, intra-field variations that can guide the more efficient application of inputs and improve productivity and farm income (Rosegrant, 2019). Previously these technologies have mainly been focused on and profitable for large scale farmers, characterized by economies of scale or barriers to entry based on expertise and financial start-up costs, which can make advanced and larger farmers more efficient than small farmers. Recently there has been more rapid development such as described above for precision agronomy, that can deliver essential information at actionable scale for small farmers.

But continued development of digital technologies and incentive policies that encourage small scale farmers to adapt and adopt digital agriculture are needed. These include speeding up cost reductions for sensors and related technologies and supporting local development partners and public-private partnerships in testing and refining technologies for context-specific applications. Innovation is especially important to integrate sensor technology and data applications into locally appropriate products and services that address problems affecting smallholder farmers. Collaboration and partnerships are essential here, including with NARS, farmer groups, non-governmental organization (NGOs), and private sector actors such as input and equipment dealers, to best scale up farming systems innovations.

The adoption of digital technology is also gaining momentum in the farm input segment of the value chain. Private and government-run management information systems can provide information on farm inputs and farm management practices such as planting methods, seeds to use, sowing time and application of fertilizers, and current market prices. Agricultural input supply companies can use digital applications to improve operations and expand outreach to meet farmers' needs, providing real-time weather information and forecasts and drought early warning systems to farmers (Rosegrant et al. 2021).

But many challenges remain to broad upscaling of digital technologies for small farmers. In sub–Saharan Africa, for example, about four hundred digital agriculture solutions are in use, but many digital solutions struggle to scale and fail to improve the lives of farmers and other end users. Beyond low adoption, governments often face broader challenges to scale. These include uneven digital access and digital literacy in their populations, low data accuracy and usability, and limited tailoring of content for local contexts. Moreover, half of sub-Saharan Africa does not have access to electric power (Tsan 2019), the average cost of entry level second generation or third generation wireless devices is 70% of the monthly income of a farmer, only about 40% of rural areas have access to 3G (Handforth 2019). Governments likely need to play a critical role in providing the core digital and data infrastructure and regulation (Goedde et al. 2021)

Value chains

Innovations are needed to better integrate small scale farmers into modernized input and farm to market value chains. Effective and accessible value chains are essential in low- and middle-income countries (LMICs) to give small-scale farms entrees to markets and access to inputs and technology at reasonable prices.

Major changes in processing, wholesale, and retail segments of the value chain are taking place in much of the developing world. The transformation includes consolidation of value-chain operations, rapid institutional and organizational change, and modernization of input and agricultural crop and livestock procurement systems. These changes include the rapid rise of supermarkets, large and modern food processors, and wholesale firms (Reardon and Timmer 2012). But many LMIC farmers are missing out on the transformation and still face barriers in using the value chain, including high transport, communication, and transaction costs.

These high costs are the result of inadequate infrastructure, lack of information, insufficient credit, and policy distortions, all of which limit or prevent small scale farms from connecting to market systems. As with farming systems, digital technologies have the potential to improve value-chain performance. Sensors linked to digital information systems can improve links between farmers and processors; reduce post-harvest losses with digitally enabled harvest loans and warehouse receipts; monitor storage conditions and track provenance to allow grading and inform consumers; reduce costs of transport; increase choice of markets and transport for farmers; and increase access to timely information (USAID 2017 cited in Rosegrant 2019).

Effective policies, technologies, and institutional arrangements to improve small farmers' access to advanced markets are also needed. Institutional partnerships are also essential, including public-private partnerships (PPP) and contract farming, and the development of farmer cooperatives that can balance the market power enjoyed by many traders through vertical integration of small-scale producers to improve commodity consolidation, agro-processing, and marketing. Aggregating mechanisms need to be put in place, for example, innovations in 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. In much of the developing world big investments in basic road infrastructure are still needed to connect farmers to markets and facilitate market development.

Scaling Up Innovation

The scaling literature distinguishes different periods in the innovation process: "(1) problem identification (2) proof of concept with evidence generated to convince stakeholders that the innovation is worthy of investment, (3) piloting of the innovation and (4) scaling, with emphasis on dissemination of the innovation to specific target groups" (IFAD, 2015, cited by Low and Thiele 2020). But many projects fail to progress beyond the pilot stage. According to Woltering et al. (2019), most pilot projects do not scale up to generate broader impact, ultimately ceasing to exist once the subsidized demonstration phase concludes and initial funding runs out.

The complexity and interconnectedness of agricultural activities involving farmers, researchers, input suppliers, markets, governments, and other actors is a major barrier to scaling innovation. Moreover, these actors operate in different contexts, with different interests, and incentives. Because of these complexities, linear approaches to scaling up innovation have achieved successes but have also often led to failures. As Shilomboleni et al. (2019) note, food security innovations in low-income rural environments have often failed to achieve substantive and lasting results. Linear approaches involving technology research and development and subsequent transfer to farmers overlook complexity and non-linear processes in smallholder agriculture, including stress factors such as climate variability and economic risks that make the uptake of new agricultural innovations more unpredictable (Shilomboleni et al. (2019). Moving away from the linear approach requires a focus on enabling conditions and strengthening capacities in innovation systems where scientists, governments, the private sector, civil society organizations, donors and investors, and farmers, can effectively collaborate and overcome both current and future agricultural development challenges (Schut et al. 2020). Stakeholders in the innovation process need to ensure that the innovation is contextually appropriate, aligned with the needs and interests of different actors, and supported by relevant policies and institutions.

(Barrett et al. 2020a; 2020b) proposed to move beyond the linear approach through "socio-technical innovation bundles," which are combinations of science and technology advances that, when combined with specific, appropriate institutional or policy adaptations, help scale up beneficial innovations in agriculture food systems. Discovering, adapting, and scaling beneficial innovations requires cooperation among social scientists, farmers, and humanists as well as engineers and natural scientists (Barrett et al. 2020b).

The "socio" part of the innovation bundles includes reforms of institutions and cultural practices, including changes in government policies in many countries (Barrett et al. 2020b). The limiting factor to innovation is often sociopolitical: insufficient leadership, political will, and willingness to find cooperative solutions. New technologies face obstacles in adapting and scaling due to biophysical, political, economic, and sociocultural factors. Combining technical advances with social and policy changes to create socio-technical innovation bundles tailored to the agri-food system context increases the likelihood of success in scaling.

The "technical" component of the innovation bundles includes new digital platforms for civic engagement and power decentralization in value chains; innovative financing structures to increase capital flow into diverse agri-food system practices and products; and advancements in plant breeding, agronomic, and food manufacturing practices to enhance the production of nutritious foods with lower water and land usage (Barrett et al. 2020b). Herrero et al. (2020) describe eight essential elements for bundling to accelerate transformation in agricultural food systems (Barrett et al. 2020b): transforming mindsets; enabling social license and stakeholder dialogue; changes in detrimental policies and regulations; designing market incentives; safeguarding against indirect, undesirable effects; ensuring stable finance; and developing transition pathways (Herrero et al. 2020).

The development and dissemination of biofortified pro-vitamin A varieties of orange-fleshed sweet potatoes (OFSP) by the International Potato Center (CIP) and national and international partners provides lessons in how to scale which demonstrates the bundling approach, although it predates the concept presented by Barrett et al. (2020b). Low and Thiel (2020) distinguish five time periods can be in the development and scaling of the OFSP innovation package: "(1) the emergence of the innovative idea (1991‑1996); (2) proving the potential of the innovation to the nutrition community (1997‑2005); (3) evaluation of the potential to scale cost-effectively (2006‑2009); (4) significant investment in research to address breeding and other bottlenecks initiated and launching of Sweetpotato for Profit and Health Initiative (SPHI) (2010‑2014) and (5) expanded dissemination at scale (2015-mid-2019)."

Intensive piloting of the new varieties at farm level was a central steppingstone to dissemination the orange fleshed sweet potato. Equally important was rigorous biomedical research that demonstrated nutritional efficacy of the new varieties. These technical steps were bundled with an array of supporting activities that were crucial to acceptance of and dissemination of the orange flesh sweet potato.

At the core of this innovation is CIP's collaboration with national sweetpotato breeding programs, which accelerated breeding and developed over 100 pro-vitamin A varieties adapted to local agro-ecologies and consumer preferences. Released in over 20 countries in Africa and South Asia, CIP and partners employ an integrated agriculture-marketing-nutrition approach, combining demand and supply side innovations. This includes seed quality and nutrition management technologies, marketing partnerships, and food processing for diversified use. Planting material distribution, combined with gender-responsive agronomic training and nutrition education, drives widespread adoption and consumption of orange-fleshed sweetpotato. It also raises awareness among caregivers about the importance of diversified diets. Promotional campaigns, cooking classes, and increased use of sweetpotato in processed food products boost consumption, demand, and market value, inspiring more farmers to cultivate it. The dissemination of planting material and training is linked to government maternal and infant health programs and schools, benefiting families at risk of vitamin A deficiency. Over 6.8 million households in Africa and South Asia now grow and consume vitamin-A-rich sweetpotato (CG 2023).

Socio-technical innovation bundles recognize the need for any innovation, whether top down or bottom up, to be supported by a wide range of enabling conditions and mutually reinforcing institutions. The bundling of innovations increases the likelihood of success in scaling and reduces the potential for trade-offs across the goals of the innovation.

Conclusions

This paper discussed key aspects of agricultural innovation systems work today including magnitude and allocation of expenditures on agricultural innovation and how innovation priorities are determined. Then we discuss areas where the innovation system could be strengthened, including modernization of plant breeding; seeking more sustainable farming systems; development of digital agriculture; enhancement of value chains; and scaling up of innovations.

Cutting across these areas, innovation is more likely to be successful with a strong focus on enabling conditions and strengthening capacities in innovation systems where scientists, governments, the private sector, civil society organizations, donors and investors, and farmers, can effectively collaborate. Stakeholders in the innovation process can help ensure that the innovation is aligned with the needs and interests of different actors and supported by relevant policies and institutions. But beyond these important principles, major challenges must be faced to accelerate the process of successful innovation.

For example, advanced digital technologies have achieved some significant successes in developing country agriculture throughout the value chain, including making the creation of new varieties more efficient and faster, providing better farmer access to inputs, improving farm level productivity, and better connecting farmers to markets. But in many regions, barriers to entry based on expertise and financial start-up costs can make advanced and larger farmers more efficient than small farmers. Continued development of digital technologies and incentive policies that encourage small scale farmers to adapt and adopt digital agriculture are needed. These policies include (a) investment in research to generate faster cost reductions for sensors and related technologies; (b) supporting local development partners and public-private partnerships in testing and refining technologies for context-specific applications; and (c) incentivizing development of the provision of contract services for mobile irrigation pumps, tractors; laser leveling and other services that are too expensive for individual small farmers to invest in. In addition, large investments will be required in many countries to provide the digital and data infrastructure to provide broad access in rural areas. The large amount of funding needed may require co-funding between public and private sources in many cases.

Reform of economic policies is also crucial. Current policies have hindered the adoption of climate-smart and resource-saving technologies by small-scale farmers and the planting of diversified nutrient-rich and other diversified crops. Massive subsidies for fertilizer, water, energy, and pesticides have led to the overuse of these inputs, causing excessive GHG emissions and environmental degradation. Needed policy reforms include (a) elimination of biased international trade policy and price support for rice, wheat, maize (and other subsidized crops); (b) phasing out of agricultural input subsidies; (c) reinvesting the resulting budgetary savings into non-distorting income support for small farmers, social protection, and agricultural research and development. With the advances in digital technology, smart cards or phones can be used for efficient transfer of income support to small farmers; and (d) implement small-scale, time-limited "smart" subsidies to facilitate the adoption of new technology and promote environmental services.

To maintain the high rates of return investment to agricultural research and development it is recommended to (a) increase investment in modernization of crop breeding; (b) further develop and institutionalize networks and programs in partnerships among CGIAR, NARS, universities, farmer-led breeding initiatives, and the private sector; (c) establish and implement rigorous procedures for outreach to farmers, consumers, and stakeholders to determine their needs for new varieties and technologies; (d) increase research funding duration from the currently prevalent short-term projects to 8-10 year programs to provide continuity, with the flexibility and accountability to adjust course depending on the evolution of research outcomes. The current funding portfolio CGIAR is well balanced across staple and non-staple crops, and support programs including resource management, agriculture health and nutrition, climate change, and policy. Most of the funding for crop and livestock breeding should go to boosting yields and production efficiency, there should be a shift on the margin to breeding for traits that directly address climate-related crop breeding, improved nutrition content, mitigation of environmental externalities.

Genetic improvement for fruits and vegetables, which are outside the CGIAR mandate can be more effectively pursued by the private sector, while CGIAR and other international agricultural programs could prioritize the development of strategies for integrated pest management, biological pest control, and improved water use efficiency, areas where private companies have limited financial incentives.

Finally, support for global multistakeholder platforms to support scaling innovations would be valuable. An example is the Food Action Alliance is a multi-stakeholder platform with a shared vision of achieving sustainable food systems through a "movement and action by actors everywhere, including countries, cities, communities, companies, civil society, consumers, producers, and workers all around the world that deliver better, faster, and at scale on food security and nutrition, inclusive growth and decent jobs, environmental sustainability, and climate resilience" (Food Action Alliance 2023)

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[i] Prasad et al. (2023) notes that the estimates are subject to a significant degree of uncertainty. Some agricultural innovation funding categories lack easily accessible data, and several countries or organizations do not report such information with sufficient detail. Analysis and estimates incorporate assumptions and extrapolations based on the best available information, including expert opinions. The detailed methodology (Dalberg Asia, 2021) provides a complete list of the specific assumptions, multipliers, and sources used in this study.

[ii] Note that all dollar values are based on 2011 PPP exchange rates, which reflect the purchasing power of currencies more effectively than do standard exchange rates because they compare the prices of a broader range of local, as opposed to internationally traded, goods and services.