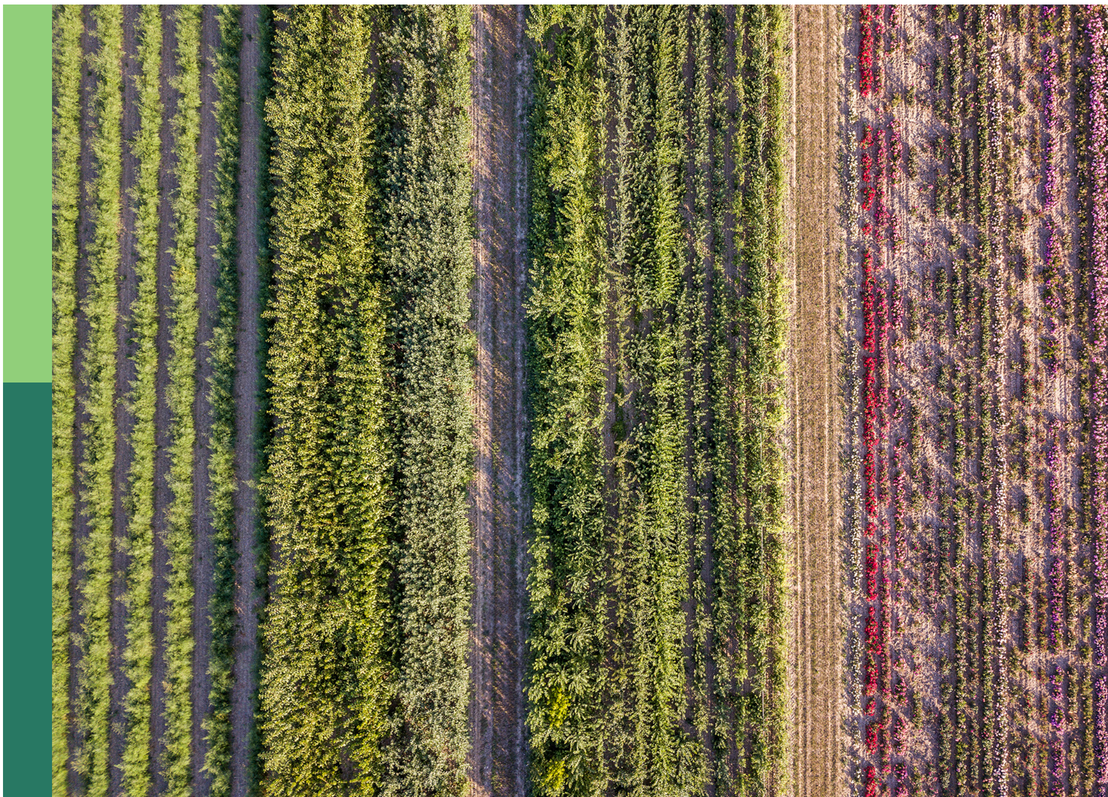
Research Topics

Improving investment in research and innovation to transform agrifood systems in the Global South

Edited by
Pablo Tittonell, P. V. Vara Prasad, Julia Compton and Ruben G. Echeverria

Published in
Frontiers in Sustainable Food Systems



ISSN 1664-8714
ISBN 978-2-8325-3829-6
DOI 10.3389/978-2-8325-3829-6

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

Improving investment in research and innovation to transform agrifood systems in the Global South

Topic editors
Pablo Tittonell — University of Groningen, Netherlands
P. V. Vara Prasad — Kansas State University, United States
Julia Compton — Independent researcher, Cardiff, United Kingdom
Ruben G. Echeverria — Bill and Melinda Gates Foundation, United States

Citation
Tittonell, P., Prasad, P. V. V., Compton, J., Echeverria, R. G., eds. (2023). *Improving investment in research and innovation to transform agrifood systems in the Global South*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-3829-6

Table of contents

05 Editorial: Improving investment in research and innovation to transform agrifood systems in the global south
Julia Compton, Ruben Echeverría, P. V. Vara Prasad and Pablo Tittonell

09 Global investment gap in agricultural research and innovation to meet Sustainable Development Goals for hunger and Paris Agreement climate change mitigation
Mark W. Rosegrant, Timothy B. Sulser and Keith Wiebe

30 Multidimensional impacts from international agricultural research: Implications for research priorities
Keith Fuglie, Keith Wiebe, Timothy B. Sulser, Nicola Cenacchi and Dirk Willenbockel

45 Investment priorities for research and innovation in urban agri-food systems: Toward more resilient cities in the Global South
Gordon Prain, David Simon, Jess Halliday and Pay Drechsel

55 Scaling up sustainability through new product categories and certification: Two cases from India
Apoorve Khandelwal, Nandini Agarwal, Bhamini Jain, Darshna Gupta, Anjaly Teresa John and Paul Farah Cox

73 A critical comparative review of evidence on alternative instruments for supporting research and innovation in agri-food systems in the Global South
Brigid Aileen Letty, Tim G. B. Hart, Simone Murugan, Theolin Naidoo, Sharad Rai, Djibril Thiam, Joshua Zake, Sershen and Irene Annor-Frempong

82 Integrated modeling framework for sustainable agricultural intensification
Molly E. Brown, Ana J. P. Carcedo, Michael Eggen, Kathryn L. Grace, Jason Neff and Ignacio A. Ciampitti

89 Innovation capacity, food system development, and the size of the agricultural research system
Alejandro Nin-Pratt and Gert-Jan Stads

108 Using machine learning to evaluate 1.2 million studies on small-scale farming and post-production food systems in low- and middle-income countries
Jaron Porciello, Leslie Lipper and Maryia Ivanina

119 Key factors for advancing innovations to scale: Evidence from multiple country case studies of agricultural innovations
Richard D. Kohl

141 **Patterns of investment in agricultural research and innovation for the Global South, with a focus on sustainable agricultural intensification**
P. V. Vara Prasad, Nirat Bhatnagar, Vineet Bhandari, George Jacob, Kaushal Narayan, Ruben Echeverría, Nienke Beintema, Paul Farah Cox and Julia Compton

159 **Estimating the intrahousehold costs and benefits of innovations to enhance smallholder farmers' resilience**
Berber Kramer, Anne G. Timu and Osman Damba

179 **Principles for guiding research and innovation toward sustainable and equitable agrifood systems**
Monika Zurek, Jonathan Wirths, Aniek Hebinck, Scarlett Crawford, Preetmoninder Lidder, P. V. Vara Prasad, Pablo Tittonell, Mario Herrero and Julia Compton on behalf of Taskforce

frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 17 October 2023
DOI 10.3389/fsufs.2023.1287451

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Ole Mertz,
University of Copenhagen, Denmark

*CORRESPONDENCE
Julia Compton
✉ jaf.compton@gmail.com

†PRESENT ADDRESSES
Julia Compton,
Independent Consultant, Cardiff, Wales, United Kingdom

Ruben Echeverría,
International Center for Tropical Agriculture (CIAT), Cali, Colombia

P. V. Vara Prasad,
Sustainable Intensification Innovation Lab, Kansas State University, Manhattan, KS, United States

Pablo Tittonell,
University of Groningen, Groningen, Netherlands;
IFAB, INTA-CONICET, San Carlos de Bariloche, Argentina

RECEIVED 01 September 2023
ACCEPTED 02 October 2023
PUBLISHED 17 October 2023

CITATION
Compton J, Echeverría R, Prasad PVV and Tittonell P (2023) Editorial: Improving investment in research and innovation to transform agrifood systems in the global south. *Front. Sustain. Food Syst.* 7:1287451. doi: 10.3389/fsufs.2023.1287451

Editorial: Improving investment in research and innovation to transform agrifood systems in the global south

Julia Compton*†, Ruben Echeverría†, P. V. Vara Prasad† and Pablo Tittonell†

Commission on Sustainable Agriculture Intensification (CoSAI), Colombo, Sri Lanka

KEYWORDS

research and innovation, investment, global south, innovation instruments and pathways, agriculture and food systems, environmental sustainability, gender and social inclusion

Editorial on the Research Topic
Improving investment in research and innovation to transform agrifood systems in the global south

1. Introduction

The agri-food sector is globally critical for tackling climate change and environmental decline, poverty and inequity, and hunger and nutrition. Achieving the Sustainable Development Goals (SDGs) will require huge increases in investment in agrifood research and innovation (ARI) (Herrero et al., 2020). Innovation is needed in policy, social institutions, finance, technology, and management practices.

This Research Topic (RT) was initiated by an international Commission on Sustainable Agriculture Intensification, CoSAI (CoSAI Secretariat, 2022), created to promote more and better innovation to support rapid sustainable and equitable transformation of agrifood systems in the Global South. This Research Topic covers three main areas that are key to decision making by research/innovation organizations and their funders (Figure 1): ARI gaps, needs and priorities; pathways, approaches and instruments; and assessment of ARI with a sustainability lens. It brings together eight articles generated from CoSAI working papers with four from an open call. The articles are rich and the findings are often surprising. Space only allows a few points: we urge readers to consult the full articles.

2. ARI investment gaps, needs and priorities

2.1. Current investment in ARI must be reoriented to transform agrifood systems

Rosegrant et al. estimate the *ARI investment gap for the Global South* at around US$10.5 billion per year, and provide a useful comparison with related estimates from other models.

Prasad et al. summarize an ambitious first attempt to estimate *current investment in ARI for the Global South*, including broader investments in innovation as well as R&D.

Despite the importance of the agrifood sector for global goals, current levels of ARI investment as a proportion of output are estimated at only two thirds of those in the energy sector. When analyzed across five domains of sustainable agricultural intensification (productivity, economics, environment, social and human; Stewart et al., 2018), <7% of ARI investment had discernible environmental aims, and only 4.5% had both environmental and social or "human" (e.g., nutrition) aims, which is extremely low.

The serious neglect of social and human aspects of ARI investment is also highlighted by Porciello et al., who used machine learning to extract information on 1.2 million ARI publications, and Brown et al., who reviewed a smaller sample of highly-cited agricultural modeling publications. Brown et al. propose a framework integrating social and demographic modeling with agricultural modeling to assess ARI investments.

These findings support international calls to massively increase and reorient ARI for sustainable and equitable agrifood systems, increasing funding for social equity, human and environmental aspects of ARI.

2.2. Conspicuous areas of underinvestment for the global south include post-harvest management, local seed systems, and (peri-)urban agriculture

Prasad et al. highlight several areas of underinvestment. Two stand out:

- ARI in *post-production issues* receives <10% of the funding for production-related ARI, although post-production accounts for the majority of food costs (Reardon et al., 2019) and is critical for food waste and the environment (Chen et al., 2020).
- Innovation *in self-saved and local seed systems* receives <0.5% of all seed innovation funding, although these are the main sources for most small-scale farmers in the Global South (Coomes et al., 2015), and a key mechanism of *in-situ* agrobiodiversity conservation (FAO, 2019).

Prain et al. review ARI investment priorities for Urban and Peri-Urban Agriculture (UPA) in the Global South, e.g., city-region planning, water and waste recycling and controlled-environment agriculture. With 70–80% of global food production consumed in cities (FAO, 2019) and 40% of global cropland located within 20 km of urban areas (Thebo et al., 2014), investment is much needed to develop circular economies with strong rural-urban interactions.

Fuglie et al. model the multidimensional impacts of agricultural productivity growth across 110 low- and middle-income countries (LMICs). Their thought-provoking findings include:

- *South Asia* is the region where agricultural productivity growth gives by far the highest returns in income growth, hunger reduction, and reductions in greenhouse gas (GHG) emissions.
- *Increasing cereal productivity* results in greater increases in diet micronutrient availability (zinc, iron and protein) than investments in other crops.
- Productivity growth *in livestock* reduces GHG emissions per unit product, but conversely *increases* the risk of hunger and overall land use.

Finally, Nin Pratt and Stads model factors affecting investment in ARI in different types of countries, especially highlighting the challenges faced by small LMICs. In a wide-ranging and thoughtful

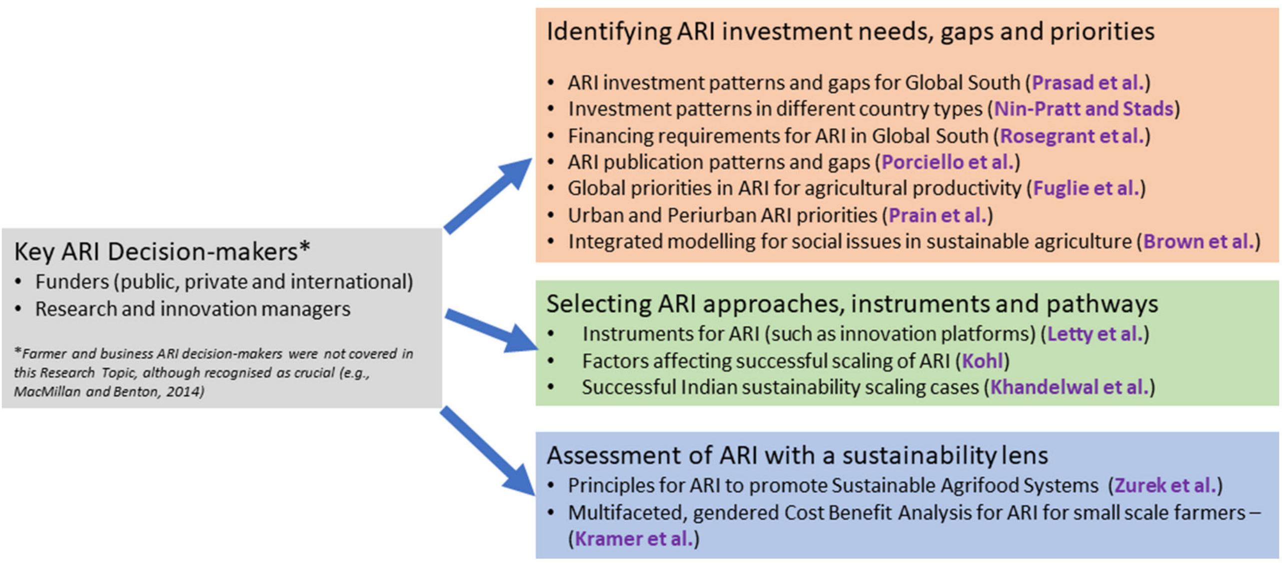


FIGURE 1
Agrifood research and innovation (ARI) for sustainable agrifood systems: mapping the contributions of the CoSAI (Commision on Sustainable Agricultural Intensification) Research Topic.

discussion, they suggest that *small LMICs may benefit from* investing in ARI capacity development and ruthless prioritization of Research Topics, along with stronger international linkages.

3. ARI pathways, approaches and instruments

Letty et al. review the main *instruments* that have been used to incentivize and support ARI in the Global South, such as innovation platforms and networks, grants, prizes, incubators and accelerators. They find that despite their potential, most of these instruments are still used in projects, and not at scale. More rigorous evaluations are needed, which should document important aspects such as social equity, financial and transaction costs.

ARI success is often judged by the success of "scaling," or wide adoption by potential users. A variety of theories and tools for scaling success have been advanced (Dror and Wu, 2020), and there is a global community of practice[1] and at least one sourcebook (Cooley and Howard, 2019). Kohl contributes to this literature by assessing six common hypotheses on "scaling success" factors against 15 case studies from seven countries. Among many interesting points are:

- The importance of individual leadership. This has gained new importance with the need for leadership to attain sustainability/equity goals alongside scaling (Lukwago et al., 2022; Boeske, 2023).
- The importance of a long-term portfolio approach, where a few big ARI successes more than compensate for many failures. Short-term project targets set by ARI funders can unintentionally undermine long-term portfolio success.

Khandelwal et al. critically discusses two fascinating sustainability scaling cases: Safe Harvest (pesticide-free produce) and Trustea (tea certification), both developed by and for the domestic market in India.

4. Assessment of ARI, with a sustainability lens

"Innovation solves problems and creates new ones" (van Noordwijk et al., 2021, p. 1). "Assessing potential trade-offs ... and unintended effects" is one of the eight *Principles for guiding research and innovation toward sustainable and equitable agrifood systems* developed and piloted by an international taskforce supported by CoSAI, together with practical guidance[2] and a simple scoring system for their application by ARI managers and funders (Zurek et al.).

Estimating costs and benefits in ARI is often based on income estimates, calculated at household level. Kramer et al. introduce a *novel method for Cost-Benefit Analysis that quantifies other welfare benefits*, such as consumption smoothing, empowerment, and time use, for individual women and men within households. The framework was tested in a case study of climate information services in Ghana.

1 https://www.scalingcommunityofpractice.com/groups/scaling-up-in-agriculture-and-rural-development/

2 https://www.youtube.com/watch?v=KwKM-Mo7hZI

5. Discussion

The findings of this Research Topic support global calls for critical re-orientation of ARI investments for transforming our agrifood systems to address SDGs and climate goals. It contributes evidence to three main areas of decision making for funders and ARI managers: how much and where to invest; what instruments and pathways may increase ARI uptake; and how to assess ARI with a sustainability lens.

A common theme is that *intentional* prioritization and management of ARI is vital to meet multiple sustainability and equity objectives. The wide adoption of Principles for ARI (Zurek et al.) would be an important step. The Principles could be combined with other tools, such as agroecological assessments (Mottet et al., 2020); the sustainable intensification assessment framework (Stewart et al., 2018) or sustainability indicators (e.g., the UN SDGs). Transparent global tracking of ARI is also important, in part to increase incentives and pressure on funders (Prasad et al.; Compton et al., 2022; FAO, 2022). Modeling, which underpins many decisions, must be "transparent and humble" (Saltelli et al., 2020; Wiebe and Prager, 2021). Finally, the Research Topic highlights major evidence gaps that persist around social equity and human aspects of ARI, and around instruments for ARI, as above (CoSAI, 2021; Letty et al.).

Author contributions

JC: Writing—original draft, Writing—review and editing. RE: Writing—review and editing. PVVP: Writing—review and editing. PT: Writing—review and editing.

Funding

Publication of this editorial was supported by Feed the Future Sustainable Intensification Innovation Lab (SIIL) and United States Agency for International Development (USAID) (Cooperative Agreement # AID-OAA-L-14-00006). The work of CoSAI (see Acknowledgments) was principally funded by the CGIAR Trust Fund (https://cgiar.org/funders), with contributions from USAID and SIIL, as acknowledged in individual papers in this Research Topic.

Acknowledgments

The guest editors wish to thank the authors and reviewers for all their contributions. This Research Topic was initiated by the

Commission on Sustainable Agriculture Intensification (CoSAI), supported by the CGIAR Research Program on Water, Land, and Ecosystems, based in the International Water Management Institute, Colombo. Detailed acknowledgments are in the final CoSAI management report (CoSAI Secretariat, 2022), along with a summary of key CoSAI achievements and links to further work.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Boeske, J. (2023). Leadership towards sustainability: a review of sustainable, sustainability, and environmental leadership. *Sustainability* 15:12626. doi: 10.3390/su151612626

Chen, C., Chaudhary, A., and Mathys, A. (2020). Nutritional and environmental losses embedded in global food waste. *Res. Conserv. Recycl.* 160, 104912. doi: 10.1016/j.resconrec.2020.104912

Compton, J., Stads, G. J., Barrett, C. B., Herrero, M., Arndt, C., Prasad, P. V. V., et al. (2022). *Global Tracking of Agrifood Research and Innovation for Meeting Food Security and Sustainable Development Goals*. Available online at: https://www.global-solutions-initiative.org/policy_brief/global-tracking-of-agrifood-research-and-innovation-for-meeting-food-security-and-sustainable-development-goals/ (accessed August 21, 2023).

Cooley, L., and Howard, J. (2019). *Scale Up Sourcebook*. West Lafayette, IN: Purdue University and African Development.

Coomes, O. T., McGuire, S. J., Garine, E., Caillon, S., McKey, D., Demeulenaere, E., et al. (2015). Farmer seed networks make a limited contribution to agriculture? Four common misconceptions. *Food Policy* 56, 41–50. doi: 10.1016/j.foodpol.2015.07.008

CoSAI (2021). *Better Instruments and Approaches are Needed to Transform Agri-Food Systems Research and Innovation. Commission on Sustainable Agriculture Intensification*. Available online at: https://www.iwmi.cgiar.org/archive/cosai/sites/default/files/CoSAI_Policy_Brief_4_AIS_v2/index.pdf (accessed October 8, 2023).

CoSAI Secretariat (2022). *Final Management Report. Colombo: Commission on Sustainable Agriculture Intensification, CGIAR Research Program on Water, Land and Ecosystems, International Water Management Institute*. Available online at: https://www.iwmi.cgiar.org/archive/cosai/sites/default/files/CoSAI-Final-Management-Report/index.pdf (accessed October 8, 2023).

Dror, I., and Wu, N. (2020). *Scaling Better Together: The International Livestock Research Institute's Framework for Scaling*. Nairobi: ILRI.

FAO (2019). *FAO Framework for the Urban Food Agenda*. Rome: Food and Agriculture Organization of the United Nations (FAO).

FAO (2022). *Introducing the Agrifood Systems Technologies and Innovations Outlook*. Rome: Food and Agriculture Organisation of the United Nations.

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Benton, T. G., Bodirsky, B. L., et al. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nat. Food* 1, 266–272. doi: 10.1038/s43016-020-0074-1

Lukwago, J., Martins, A. M. D. A., and Tefera, O. (2022). Drivers and barriers in developing sustainability leadership – a case of natural scientists at Ugandan universities. *Int. J. Sust. Higher Educ.* 24, 895–910. doi: 10.1108/IJSHE-08-2021-0327

MacMillan, T., and Benton, T. G. (2014). Agriculture: engage farmers in research. *Nat. News* 509, 25. doi: 10.1038/509025a

Mottet, A., Bicksler, A., Lucantoni, D., De Rosa, E., Scherf, F., Scopel, B., et al. (2020). Assessing transitions to sustainable agricultural and food systems: a tool for agroecology performance evaluation (TAPE). *Front. Sust. Food Sys.* 4, 579154. doi: 10.3389/fsufs.2020.579154

Reardon, T., Echeverria, R., Berdegué, J., Minten, B., Liverpool-Tasie, S., Tschirley, D., et al. (2019). Rapid transformation of food systems in developing regions: highlighting the role of agricultural research and innovations. *Agric. Syst.* 172, 47–59. doi: 10.1016/j.agsy.2018.01.022

Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, E., Didier, M., et al. (2020). Five ways to ensure that models serve society: a manifesto. *Nature* 582, 482–484. doi: 10.1038/d41586-020-01812-9

Stewart, Z. P., Middendorf, B. J., Musumba, M., Grabowski, P., Palm, C., Snapp, S., et al. (2018). *SIToolKit. com. Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification*. Manhattan, KS: Kansas State University.

Thebo, A. L., Drechsel, P., and Lambin, E. F. (2014). Global assessment of urban and peri-urban agriculture: irrigated and rainfed croplands. *Environ. Res. Lett.* 9, 114002. doi: 10.1088/1748-9326/9/11/114002

van Noordwijk, M., Wainaina, P., Foundjem, D., Mandiefe, S. P., and Tanui, J. (2021). "Innovation in a systems perspective," in *Tree Commodities and Resilient Green Economies in Africa*, eds. P. A. Minang, L. A. Duguma, and M. van Noordwijk (Nairobi: World Agroforestry).

Wiebe, K., and Prager, S. (2021). Commentary on foresight and trade-off analysis for agriculture and food systems. *Q. Open* 1, qoaa004. doi: 10.1093/qopen/qoaa004

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 05 October 2022
DOI 10.3389/fsufs.2022.965767

Check for updates

OPEN ACCESS

EDITED BY
Julia Compton,
Independent Researcher, Cardiff, United Kingdom

REVIEWED BY
Ruediger Schaldach,
University of Kassel, Germany
James Jones,
University of Florida, United States

*CORRESPONDENCE
Mark W. Rosegrant
m.rosegrant@cgiar.org

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 10 June 2022
ACCEPTED 13 September 2022
PUBLISHED 05 October 2022

CITATION
Rosegrant MW, Sulser TB and Wiebe K (2022) Global investment gap in agricultural research and innovation to meet Sustainable Development Goals for hunger and Paris Agreement climate change mitigation. *Front. Sustain. Food Syst.* 6:965767. doi: 10.3389/fsufs.2022.965767

Global investment gap in agricultural research and innovation to meet Sustainable Development Goals for hunger and Paris Agreement climate change mitigation

Mark W. Rosegrant*, Timothy B. Sulser and Keith Wiebe

International Food Policy Research Institute (IFPRI), Washington, DC, United States

This paper provides estimates of the global investment gap in agricultural research and development (R&D) and innovation. The investment gap is defined as the additional annual investments required to end hunger in 2030 (Sustainable Development Goal SDG2) and to put agriculture on the pathway to the Paris Agreement target for 1.5°C increase over pre-industrial temperature levels. The investment gap is projected relative to a reference scenario with projections to 2030 using an integrated economic-biophysical model of the global agri-food system. In addition to showing the impacts on hunger, the modeling results are used to simulate the effect of the gap-closing investments on greenhouse gas (GHG) emissions from agriculture. In addition to projecting the impacts of overall investment in agricultural R&D on productivity and environmental outcomes, the analysis assesses the contributions of different types of innovative technologies and farming systems to the environmental outcomes, especially technologies that contribute to sustainability outcomes. Sustainability-oriented technologies and management practices examined include conservation tillage, nitrogen-use efficiency, improved livestock management, and other climate-smart technologies. The projected results show that additional agricultural R&D investments of USD 4 billion per year above baseline investments together with USD 6.5 billion per year invested in technical climate-smart options, can reduce hunger to 5% globally and achieve 2030 GHG emission reductions consistent with the Paris Agreement 2°C and 1.5°C pathways to 2030.

KEYWORDS

agricultural research and innovation, climate change, hunger, investment, sustainable development goals (SDGs)

Introduction

If the world is to achieve the Sustainable Development Goal 2 (SDG2) (United Nations 2022), to end hunger and succeed in stabilizing global warming at below 2°C, and adapt to the climate change that this warming will bring, agricultural systems must transform significantly by 2030. This 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). Developments in consumption patterns are positive in some respects but negative in many others. There is increased consumption of fruits and vegetables; growing demand for sugar, fats, and oils; and rapid growth in meat consumption and therefore higher demand for feed grains or other livestock feeds (Godfray et al., 2010; Kearney, 2010; Thornton, 2010; Rosegrant et al., 2017). As these demands put pressure on food systems and sustainable food production growth also faces challenges from climate change, with higher temperatures, changing precipitation patterns, as well as a likely increase in weather variability (Smith et al., 2018; Mbow et al., 2019).

Concurrently, 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.

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 research pulls together multiple modeling techniques to estimate the size of that investment.

Specifically, this paper uses integrated economic and biophysical modeling and assessment of climate-smart and resource-saving technical options 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 is 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 temperature increase below 2°C (Paris Agreement).

Background

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 follow:

- Public and private investments in agricultural research and development (R&D) for the Global South, which consists of sub-Saharan Africa, Latin America and the Caribbean, Pacific Islands, and the low- and middle-income countries in Asia, the Middle East, and North Africa.
- Investments to support the adoption of technical mitigation options for climate change mitigation in agriculture through carbon payments or other forms of targeted subsidies or payments of environmental services.

The analysis of agricultural R&D investments covers the key actors for the Global South, the international public research institutions of the CGIAR (a global partnership of international agricultural research centers, formerly known as the Consultative Group for International Agricultural Research), national agricultural research systems (NARS), and the private sector. The CGIAR operates through research partnerships at 15 different international agricultural research centers. CGIAR has more than 9,000 staff working in 89 countries around the world (CGIAR, 2022). NARS are national public research institutes based in the Global South, which primarily conduct locally relevant research for the benefit of their own nations. Private sector investments included here are those directly allocated to the Global South, including expenditures by international companies and national companies in the Global South. Analysis of the investment requirements and investment gap up to 2030 uses 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. The SDG2 (zero hunger) and the Paris Agreement (UNFCCC, 2020) on climate change provide the specific sustainability context in which the investment gaps are evaluated. The targets and indicators of progress used to assess the effectiveness of investments in addressing the gaps follow.

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 the 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 the 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 (REF_HGEM).

Paris Agreement. The Paris Agreement provides broad targets for mitigation. It 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-carbon dioxide (CO_2) GHG emissions from agriculture by 1,000 million tons of CO_2 equivalents ($MtCO_2eq$)/year by 2030 to limit warming in 2100 to 2°C above pre-industrial levels. This target 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 $MtCO_2eq$/year in 2030; van Vuuren et al. (2011) estimated 1,370 $MtCO_2eq$/year; and Wise et al. (2014) estimated 920 $MtCO_2eq$/year (all cited in Wollenberg et al., 2016). We adopt this target as the mitigation requirement for investment in sustainable agriculture intensification. Target estimates for non-CO_2 mitigation in 2050 are not available and targets for a 1.5°C pathway are also unavailable. Targets have been estimated for CO_2 emissions that are consistent with the 1.5°C pathway, but not for a 2°C pathway. Rogelj et al. (2018) estimated targets for these CO_2 emissions consistent with the 1.5°C pathway based on the set of scenarios outlined by the Intergovernmental Panel on Climate Change (IPCC, 2018). The target is to sequester 100 $MtCO_2$/year by 2030, and 2,300 $MtCO_2$/year by 2050. These estimates are based on a low-overshoot scenario and are at the upper end of the required reductions outlined in these scenarios (Rogelj et al., 2018; McKinsey and Company, 2020). SDG13 is also related to climate change. It sets forth targets for climate action focused primarily on policies for 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. This paper does not address these policies directly.

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 (CH_4) and nitrous oxide (N_2O)] emissions—the analysis shows the impacts of these investments on 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 potential gap-closing investments.

Methodology

Economic and biophysical modeling

The primary tool for the scenario analysis is IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) framework, an integrated modeling system that combines information from climate models (Earth System Models, ESMs), crop simulation models (Decision Support System for Agrotechnology Transfer—DSSAT), 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 (Robinson et al., 2015) with a high level of disaggregation across 158 countries, 154 water basins, and 60 commodities. ESMs provide monthly rainfall and temperature data under alternative climate change scenarios, the results of which were downscaled to the pixel level for input into the crop models. The hydrological and water supply and demand models then determine the runoff available for crop production based on the downscaled rainfall data along with interactions across other economic sectors (industrial, domestic, livestock, and irrigation).

DSSAT, developed by Jones et al. (2003), and frequently updated since then, integrates crop, soil, and weather databases into standard formats for use by crop models and other applications. Weather statistics, including the availability of water from rainfall and runoff and temperature from climate models are incorporated in order to estimate crop yield impacts under existing and various future climate scenarios. The biophysical models are then used to estimate the impacts of climate change (through changing temperature and water availability) on crop yields. All crop yield simulations, both in the reference case and any alternative scenarios, are within bounds of known biophysical limits through an iteration check against the Global Yield Gap Atlas (van Ittersum et al., 2013). Biophysical yield shocks from climate change are then input into the IMPACT partial equilibrium model. Climate change shocks induce economic feedback effects in the model. Taking the example of an initial negative impact on yields, the drop in supply will induce higher commodity prices, which in turn generate yield and area increases in the model, which partly compensate for the initial biophysical shock.

IMPACT is linked to a global general equilibrium model, GLOBE (Willenbockel et al., 2018). 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. 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. The feedback from GLOBE to IMPACT captures the endogenous effect of changes in income on food demand, food prices, and hunger. The output from the above modeling provides the drivers for further analyses that estimate the effects of alternative scenarios on the share and number of hungry people and GHG emissions.

Analysis of GHG emissions

The GHG emissions post-processor gives the GHG impacts generated by modeled changes in crop and livestock production systems caused by agricultural productivity growth in the different scenarios. The empirical approach to estimating GHG emissions uses IPCC Tier 1 factors for GHG emissions (IPCC, 2006; Yan et al., 2009). The Tier 1 method, which provides a default emission factor and scaling factors, is applied to countries in which country-specific emission factors do not exist. The Tier 2 method is the same as the Tier 1 method but requires that country-specific emission factors and/or scaling factors be used. The Tier 1 method is the most feasible for application at a global scale for a modeling analysis such as this paper because Tier 2 factors are not available for most countries (Yan et al., 2009). The GHG emissions are estimated from three subcategories: synthetic fertilizers (N_2O), rice cultivation (CH_4), and enteric fermentation (CH_4) in livestock. To simulate emissions, we employ the IPCC Tier 1 factors for direct N_2O emissions arising from mineral nitrogen (N) fertilizer application to managed soils. The CO_2 equivalent (CO_2eq) for these emissions is computed by multiplying the amount of the GHG by its global warming potential.

The IPCC Tier 1 default factors for direct N_2O emissions arising from mineral N fertilizer application are 0.01 kg N_2O-N per kg N fertilizer applied to managed soils and 0.003 kg N_2O-N per kg N fertilizer applied to irrigated rice. These factors are multiplied by the N fertilizer consumption projections for each country and each crop/commodity. Note that the N_2O emissions we estimate exclude the indirect N_2O emissions from N leaching and runoff and atmospheric N deposition.

To estimate CH_4 emissions from rice production, we combine crop/commodity yield projections with Tier 1 emission factors from Yan et al. (2009), enhanced by scaling factors. 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 drainages), 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 are 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 are estimated based on animal number projections (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) are 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 are computed. The relationship between changes in crop area and livestock production and total cropland and forest area are derived from simulations that linked IMPACT and LandSHIFT, a land use and land cover change model (Schaldach et al., 2011). The estimated changes in forest area driven by changes in area and livestock production under alternative scenarios are then multiplied by a coefficient for estimated GHG sequestration per unit of forest area to compute the carbon sequestration generated by the investment scenarios. This coefficient varies by type of forest and region. Sequestration rates for afforestation/reforestation range within 0.8–2.4 t/ha/year in boreal forests, 0.7–7.5 t/ha/year in temperate regions, and 3.2–10 t/ha/year in the tropics (Brown et al., 1996). Given these ranges, we utilize a medium level of sequestration per hectare of forests of 6 $MtCO_2$/ha/year to compute global sequestration of CO_2 under the agricultural R&D investment scenarios.

Investment scenarios

The scenarios utilize key elements of IPPC scenarios. 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, 2015). Population growth and GDP growth assumptions in the reference scenario are drawn from SSP2, which is a middle-of-the-road scenario based on historical trends and potential changes in trajectories in economic and demographic growth. The SSP2 scenario corresponds to the medium variant of IIASA-VID-Oxford population projections, where global population reaches 8.3 billion by 2030 with a global GDP of US$143 trillion. Under SSP2, expected changes in population and economic growth vary substantially by region. Population growth is concentrated in the developing world, where population grows at more than one percent per year adding, by 2030, almost 1.4 billion people globally, compared to only 0.1 billion in developed countries. Economic growth is also faster in developing countries, with an average annual growth rate of 5% compared to 2% in developed countries (Mason-D'Croz et al., 2019).

The second key component in the IPCC scenarios is the Representative Concentration Pathways (RCPs), which represent potential GHG emission levels in the atmosphere and the subsequent increase in solar energy that would be absorbed (radiative forcing). There are four RCPs, 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. Through 2030, there are limited differences in atmospheric concentration of GHGs across the four RCPs ranging from concentration levels between 445 ppm and 480 ppm in 2030 compared to approximately 375 ppm in 2005. Radiative forcing in 2030 ranges from 2.9 W/m2 to 3.3 W/m2 compared to 1.9 W/m2 in 2005. The RCPs begin to diverge more significantly by mid- and end-of-century. For this analysis we use RCP 8.5, the most severe of the RCPs, which has a radiative forcing pathway leading to 8.5 W/m2 (approximately 1,370 ppm CO_2 eq) by 2100.

Following the 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 in 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 GHG emissions from agriculture and deforestation.

The impact of overall agricultural R&D investments is captured in the model in terms of productivity gains and subsequent impacts on environmental and other outcomes. In this article 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 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 et al., 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 Pardey et al. (2006) and Fuglie (2016).

Beyond the reference scenario, we have developed an R&D investment–yield model to assess the investment required to achieve projected growth in agricultural productivity under the alternative investment scenarios. Investments in research take time to bear fruit, as new ideas can take years to develop and spread. To capture these lags, we utilize an investment–yield estimation model based on the perpetual inventory method, in which 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 it decays. The lag structure in the perpetual inventory method used here follows a gamma distribution in which R&D investments reach peak impact 10–15 years after initial investment and then decline over time to zero impact 10–15 years after peak impact. With regionally differentiated elasticities of yield with respect to research and decay rates, these imputed lag structures vary by region according to existing R&D capacity and the potential trajectories for each region. The elasticity of yield with respect to research measures the percentage change in yields with respect to the stock of knowledge, which is explained in the paragraph above. See Appendix J of Rosegrant et al. (2017) for parameters used in the perpetual inventory method. This approach allows us not only to estimate the baseline costs in research implied under the reference scenario to 2050 but also to estimate the additional investments needed to adapt to climate change and make progress toward selected SDGs. 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.

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. In addition to food security impacts, the impact on emissions of CO_2, non-CO_2, and those 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 N use efficiency (using less N per unit of output), and by changing cropping and livestock production patterns.

Along with a reference business-as-usual scenario, alternative agricultural R&D investment scenarios are analyzed in this article. The scenarios for higher investments in agricultural R&D include international public research institutions of the CGIAR, national agricultural research

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

RCP8.5, Representative Concentration Pathway 8.5; HGEM, HadGEM global circulation model; R&D, research and development; NARS, national agricultural research systems; CGIAR, a global partnership of international agricultural research centers; REFF, research efficiency; and PRIV, private investment.

systems (NARS), research efficiency investments, and the private sector (Table 1).

For the reference scenario, **REF_HGEM**, investments in agricultural R&D by CGIAR are projected to average USD 1.7 billion per year during 2015–2050 in real 2005 dollars, while annual NARS investment in the Global South averages USD 6.4 billion per year (Table 2). 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 largest 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 (Table 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. Yield effects for these alternative scenarios are implemented by increasing yield growth rates relative

TABLE 2 Average annual investments in the Global South in the reference scenario (REF_HGEM), 2015–2050 (billion 2005 USD).

Region	R&D			
	CGIAR	NARS	PRIV	Total
EAP	0.07	1.54	0.74	2.35
SAS	0.26	0.71	0.6	1.57
SSA	1.11	1.11	0.05	2.27
MEN	0.09	1.41	0.14	1.64
LAC	0.2	1.59	0.21	2.00
DVG	1.73	6.36	1.74	9.83

Figures are average annual investments over 2015–2050. **HIGH**, **HIGH+NARS**, and **HIGH+NARS+REFF** 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; and DVG, Global South.

to reference yield growth rates. 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, an initiative of the Policies, Institutions, and Markets (PIM) research program of the CGIAR (see Prager and Wiebe, 2021). 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.

Scenario **HIGH+NARS+REFF** adds investments in higher research efficiency. Research efficiency is gained through advances in breeding techniques, including in genome editing technology, 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 (Waltz, 2018; Pourkheirandish et al., 2020; Zhu et al., 2020). For example, Lenaerts et al. (2018) show that a reduction in time of breeding through one technique, rapid generation advance, can generate an increase in economic benefits of 26%, 36%, and 47% with a saving of 3, 4, and 5 years, respectively, at a discount rate of 8%. Falck Zepeda et al. (2012) show that regulatory costs and time lags of 2 years delay would reduce the net present benefit for the adoption of various crop varieties by 23–71%; eliminating those delays and excess costs would increase profits by comparable amounts. Based on these studies, research efficiency is assumed to increase the yield impact of investments by 30%, and the maximum yield improvement is achieved by 2040, 5 years earlier than in the **HIGH** scenario. Investment in increased research efficiency adds another USD 0.42 billion per year to this scenario.

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 the 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%. The private sector accounts for 13% of the additional investments in this scenario.

Technical mitigation options

The analysis of technical options for GHG emissions reduction 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 management of cropland, rice, pasture, and livestock, as defined in IPCC publications (Smith et al., 2007, 2014; IPCC, 2014).

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. 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 the production of fertilizer and other inputs and value chain emissions are not included. The technical options considered follow:

- 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, new N-use-efficient crop varieties, and stabilized N sources (polymer-coated urea and nitrification inhibitors).
- Improved rice management for reduction of CH_4 emissions. This includes mid-season 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 the use of legumes.
- Livestock management, which reduces 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 Smith et al. (2008, 2018), Del Grosso and Cavigelli (2012), Smith et al. (2013), Havlík et al. (2014), IPCC (2014); Beach et al. (2015), Herrero et al. (2016), Wollenberg et al. (2016), Frank et al. (2018), IPCC (2018), and EPA (2019). Key parameters considered in the assessment include the potential savings in tCO_2eq per hectare or per animal unit from the 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, the technologies are assumed to be yield-neutral, so the costs do not include revenue changes for farmers due to possible productivity increases or decreases related to the application of a technology (Frank et al., 2018). For any given technology, this assumption could lead to over- or under-estimation of the cost of GHG emission reductions. Future research that rigorously assesses the yield impacts could allow this assumption to be dropped. The assumptions regarding the range of values for the key parameters are shown in Table 3.

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 the adoption of technical mitigation options at a carbon price of USD 70 per tCO_2eq. This carbon price was chosen for assessment based on a 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 Del Grosso and Cavigelli, 2012; Smith et al., 2014; Beach et al., 2015; Frank et al., 2018).

Based on these parameters we compute the annual costs of potential mitigation in $MtCO_2eq$ and of investment in mitigation in 2030 and 2050 in million USD. The key parameters vary across sources and different ranges are reported in many of the sources. To capture this variability, calculations are made for a series of combinations of the parameters to assess a distribution of potential outcomes. These results allow us to

TABLE 3 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 per tCO_2eq)*	*(USD per tCO_2eq)*	*(tCO_2eq per ha per year)*	*(tCO_2eq per ha per year)*	*(tCO_2eq per ha per year)*
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)
	(USD per tCO_2eq)	*(USD per tCO_2eq)*	*Global South*
Livestock sector	8–12	9–13	
Improved feeding practices, additives, etc.			5–10
Manure management			2–4
Breeding and long-term management			2–4

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

10.3389/fsufs.2022.965767

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.

Results and discussion

Investment scenarios for agricultural R&D

Projected percentage increases in crop and livestock production under the investment scenarios relative to the reference scenario (**REF_HGEM**) are shown in Figures 1, 2. The regions assessed 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; and DVG, Global South (the total of the other regions). Agricultural production growth in SSA 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 production growth in SSA are projected to grow faster relative to the reference scenario than in other regions. Crop and livestock production in SAS will also grow rapidly. There is strong growth in MENA in crop production in percentage terms, from a low reference level; LAC has substantial growth in livestock production; and EAP has relatively slow growth in both crop and livestock production, from very high reference levels.

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 the FAO prevalence of undernourishment metric (FAO, 2008). The number of hungry people is then computed as the share of people at risk of hunger multiplied by the population. The results for the impact of the investment scenarios are shown in Table 4.

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. 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 at risk of hunger in EAP, SAS, and LAC.

However, SSA remains well above the SDG2.1 target with an 11.8% share at risk of hunger in 2030, although this is a major improvement relative to its 24.3% share at risk of hunger in 2010. After 2030, the number of hungry people 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 (World Bank, 2012).

Along with the progress in achieving global hunger goals, the investment scenarios generate large economic returns. The 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 national average per capita income by 1.9% in 2030 and 5.9% in 2050 relative to business as usual (Tables 5, 6). The increases in investment in SSA generate the highest proportional per capita income gains among the various regions: 8% by 2030 and 23.5% by 2050.

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 (Table 7). Climate change reduces yields relative to a counterfactual climate scenario that follows a no-climate change (**NoCC**) pathway, assuming a constant climate after 2015, with atmospheric concentration of GHGs remaining at 2015 levels. Including both the biophysical impacts and the induced responses described in the methodology section, climate change as specified in **REF_HGEM** reduces global average crop yields compared to NoCC in 2050 scenario by 8.8% for cereals and oilseeds, 6.5% for roots and tubers, 2.9% for fruits and vegetables, and 1.9% for pulses. The reduced yields due to climate change result in increasing prices under **REF_HGEM**. Cereal prices increase by 43% between 2015 and 2050, oilseeds by 32%, roots and tubers by 42%, fruits and vegetables by 39%, and pulses by 21%. The scenarios with higher investment in R&D result in substantially lower prices for all commodities compared to the reference scenario. For example, under **HIGH+NARS+REFF+PRIV** the price for oil crops decreases on average by about 21% compared to **REF_HGEM** in 2050, whereas the decrease is over 43% for roots and tubers, 39% for cereals, and 36% for meat (Table 7). Thus, this level of investment is projected to eliminate or greatly reduce the commodity price increases from 2015 to 2050 caused by climate change.

Although this paper focuses on SSP2 and RCP8.5, a sensitivity analysis run for another recent publication using IMPACT shows that the impacts of investments in agricultural R&D on hunger have a robust effect across the range of potential

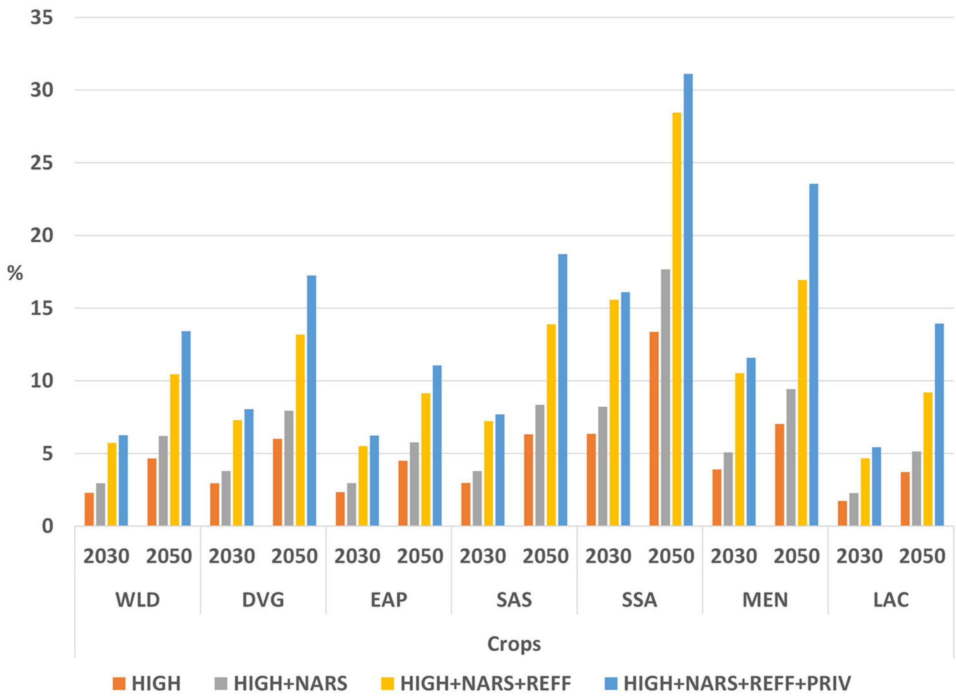


FIGURE 1
Percent changes in total crop production under alternative R&D investment scenarios compared to the reference scenario. WLD, world; DVG, Global South; EAP, East Asia and Pacific; SAS, South Asia; SSA, sub-Saharan Africa; MEN, Middle East and North Africa; and LAC, Latin America and the Caribbean. Source: IMPACT model.

climate and socioeconomic futures. Sulser et al. (2021) ran scenarios with combinations of socioeconomic assumptions for SSP1, SSP2, and SSP3, and climate assumptions with 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% and 30% in 2030 and 2050, respectively, relative to the reference scenario. 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 15–28%, relative to the reference scenario, and of 20–31% in 2050 for the **HIGH**, **HIGH+NARS**, and **HIGH+NARS+REFF** scenarios (Table 4).

GHG emission reductions through productivity growth

Total global GHG emissions from all sources were 52,000 $MtCO_2eq$ 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 $MtCO_2eq$ in 2015. IPCC (2014) estimates the total direct agricultural emissions to be in the range of 4,300–5,300 $MtCO_2eq$/year, with 95% confidence interval of 3,900–7,000 $MtCO_2eq$/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 25–42%. 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 including deforestation and peatland degradation, and 5–10% from supply chain activities (Mbow et al., 2019). The focus of this article 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 article. Although agricultural land also generates large CO_2 fluxes both to and from the

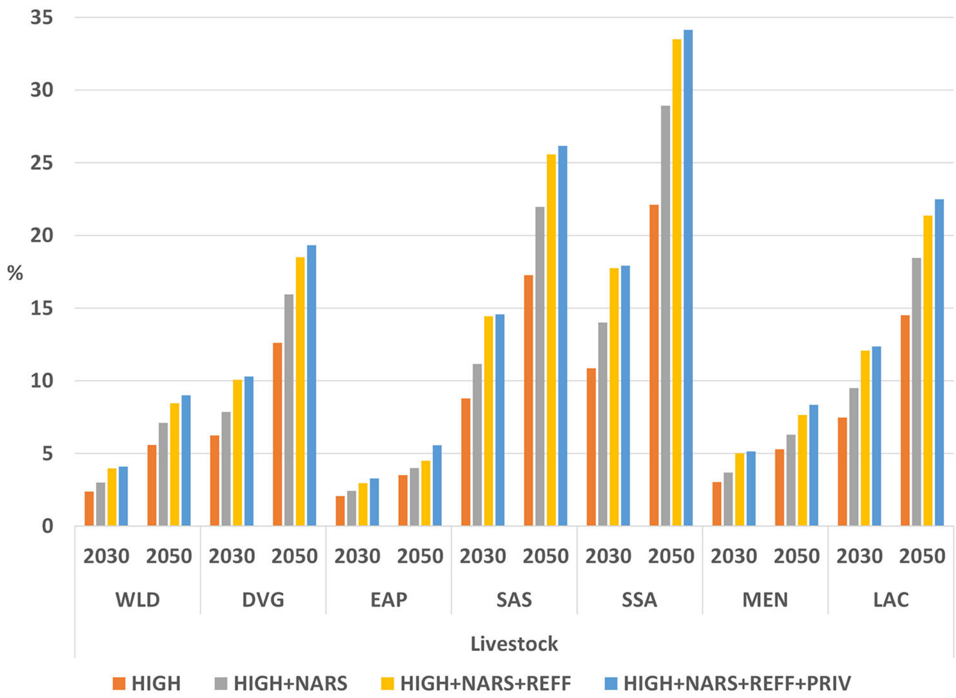


FIGURE 2
Percent changes in total livestock production under alternative R&D investment scenarios compared to the reference scenario. WLD, world; DVG, Global South; EAP, East Asia and Pacific; SAS, South Asia; SSA, sub-Saharan Africa; MEN, Middle East and North Africa; and LAC, Latin America and the Caribbean. Source: IMPACT model.

atmosphere *via* photosynthesis and respiration, this flux is nearly balanced on existing agricultural land. Substantial carbon releases, however, result from the conversion of forested land, which is accounted for under the land-use change category.

In the reference scenario, deforestation due to agricultural production for 2015–2030 is projected to be 9 million hectares (Mha)/year, and 7.3 Mha/year for 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/year, which is consistent with the available evidence. According to FAO (2020), the annual global rate of deforestation was 10 Mha/year for 2015–2020, and it is estimated that 80% of global deforestation, 8 Mha/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/year for 2015–2030 and 1 Mha/year for 2030–2050. Thus, under **HIGH+NARS+REFF+PRIV**, the projected annual average rate of deforestation is 8.1 Mha/year for 2015–2030 and 6.3 Mha/year for 2030–2050.

The **HIGH+NARS+REFF+PRIV** scenario contributes to non-CO_2 emission reductions of 291 $MtCO_2eq$/year by 2030, relative to the reference scenario. This is due to lower N_2O release from fertilizer use and reduced CH_4 from rice and livestock production (Table 8). The scenario also achieves CO_2 emission reductions of 111 Mt/year from the prevention of deforestation due to productivity growth that results in slower expansion of cropland.

GHG emission reductions and sequestration through adoption of technical options

The results from the agricultural R&D scenarios show that, in addition to coming close to meeting the SDG2 target of ending hunger, the investments of **HIGH+NARS+REFF+PRIV** make important contributions to reducing GHG emissions, but do not achieve the CO_2 or non-CO_2 emission reductions necessary 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. It is assumed that the GHG

TABLE 4 Risk 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
	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
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
	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

Source: IMPACT model.
WLD, world; DVG, Global South; EAP, East Asia and Pacific; SAS, South Asia; SSA, sub-Saharan Africa; MEN, Middle East and North Africa; and LAC, Latin America and the Caribbean.

emission reductions from technical options are additive to the GHG emissions reductions generated by the agricultural R&D scenarios. Figures 3A–C show the distribution of estimated potential mitigation of GHG emissions from technical options at a carbon price of USD 70 per tCO_2eq. Figure 4 shows the investment required to generate this level of mitigation.

The mean non-CO_2 technical mitigation economic potential in 2030 is 714 $MtCO_2eq$/year, with a range of 606–815 $MtCO_2eq$/year; the mean potential in 2050 is 783 $MtCO_2eq$/year, with a range of 647–901 $MtCO_2eq$/year (Figure 3A). Comparisons with the literature are not precise because of the different methods employed for these estimations but are nevertheless useful. Del Grosso and Cavigelli (2012) estimate that the potential for non-CO_2 agricultural mitigation from technical options at a carbon price of USD 50 per tCO_2eq is 693 $MtCO_2eq$/year in 2030; EPA (2019) estimates savings of 593 $MtCO_2eq$/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 and 800 $MtCO_2eq$/year at USD 40 and 100 per tCO_2eq, respectively, and about 850 $MtCO_2eq$/year at USD 100 per 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 4. 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 and 100 per tCO_2eq. Although the total cost of mitigation at USD 50 per tCO_2eq is of course lower than for USD 70 per tCO_2eq, at USD 3.1 billion per year, the mean potential savings is only 483 $MtCO_2eq$/year in 2030, far below the non-CO_2 agricultural mitigation needed to be consistent with the 2°C climate change pathway. At USD 100 per tCO_2eq the mean potential non-CO_2 technical mitigation economic potential in 2030 is 887 $MtCO_2eq$/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. The potential for global CO_2 sequestration from the implementation of the same technical mitigation options described above for non-CO_2 emissions reductions is shown in Figure 3B. Combined total technical mitigation potential includes the values for non-CO_2 GHG and CO_2 emissions (Figure 3C). The total CO_2 technical mitigation

TABLE 5 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	9.8	5.4	8.8	2.7	2.0	10.0	10.0
2030	REF_HGEM	17.2	12.4	22.3	6.9	3.7	17.0	16.9
	HIGH	0.5%	0.8%	0.5%	1.1%	3.6%	0.6%	0.2%
	HIGH+NARS	0.6%	1.0%	0.6%	1.4%	4.5%	0.8%	0.3%
	HIGH+NARS+REFF	1.1%	1.8%	1.1%	2.5%	7.8%	1.3%	0.5%
	HIGH+NARS+REFF+PRIV	1.2%	1.9%	1.3%	2.7%	8.0%	1.5%	0.5%
2050	REF_HGEM	24.8	19.6	35.3	13.2	7.2	25.8	25.7
	HIGH	1.8%	2.6%	1.3%	3.1%	11.9%	1.7%	0.7%
	HIGH+NARS	2.3%	3.3%	1.6%	3.8%	14.9%	2.1%	0.8%
	HIGH+NARS+REFF	3.3%	4.8%	2.4%	5.6%	21.5%	3.0%	1.2%
	HIGH+NARS+REFF+PRIV	4.1%	5.9%	3.0%	7.7%	23.5%	4.1%	1.7%

Source: IMPACT model.
Projected value for SSP2 under REF_HGEM but 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; and LAC, Latin America and the Caribbean.

TABLE 6 Regional increase in GDP under different 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
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

Source: IMPACT model.
WLD, world; DVG, Global South; EAP, East Asia and Pacific; SAS, South Asia; SSA, sub-Saharan Africa; MEN, Middle East and North Africa; and LAC, Latin America and the Caribbean.

potential has a mean of 1,868 $MtCO_2eq$/year in 2030, with a range of 1,613–2,417 $MtCO_2eq$/year; and the corresponding values for 2050 are 2,148 and 1,733–2,511 $MtCO_2eq$/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 (management of cropland, rice, pasture, and livestock) of approximately 1,575 and 1,950 $MtCO_2eq$/year at USD 50 and 100 per tCO_2eq, respectively (estimated from Smith et al., 2014: figure 11.13).

The mean results for total CO_2 GHG emissions reductions from Figure 3C are further broken down by technical options in Table 9. The results show that the projected economic mean potential non-CO_2 GHG emissions reductions from technical options in agriculture are 1,868 and 2,148 $MtCO_2eq$/year in 2030 and 2050, respectively.

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 can provide useful context. Results from these studies are summarized in Table 10.

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 of about USD 39–50 billion are required. Investments and policies considered include agricultural R&D,

TABLE 7 Global aggregated commodity prices, percent difference relative to REF_HGEM in 2030 and 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%
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%

Source: IMPACT model.

TABLE 8 Projected GHG emissions reductions and sequestration per year from agriculture due to investments in productivity growth, HIGH+NARS+REFF+PRIV, relative to REF_HGEM. Numbers in parentheses are percent change compared to REF_HGEM.

	$MtCO_2eq$/year	
Emissions sources	**2030**	**2050**
Fertilizer (N_2O)	110 (14.0)	131 (14.1)
Rice (CH_4)	27 (5.3)	53 (10.4)
Livestock (CH_4)	154 (6.6)	313 (12.7)
Total non-CO_2 GHG emissions reduction	291 (8.0)	497 (12.7)
Reductions in carbon emissions due to less land-use change	111 (1.1)	248 (2.5)

Source: IMPACT modeling analysis.

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 for 2015–2030. 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, improve returns from sales, and support the mix of services provided by small- and medium-sized enterprises, 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 for 2006–2050 would require increased R&D adaptation investments for 2020–2040 totaling USD 187–1,384 billion (in 2005 USD purchasing power parity). The 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) 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 for 2000–2019 was USD 50–70 billion in 2019 constant dollars. Classifying spending estimates by

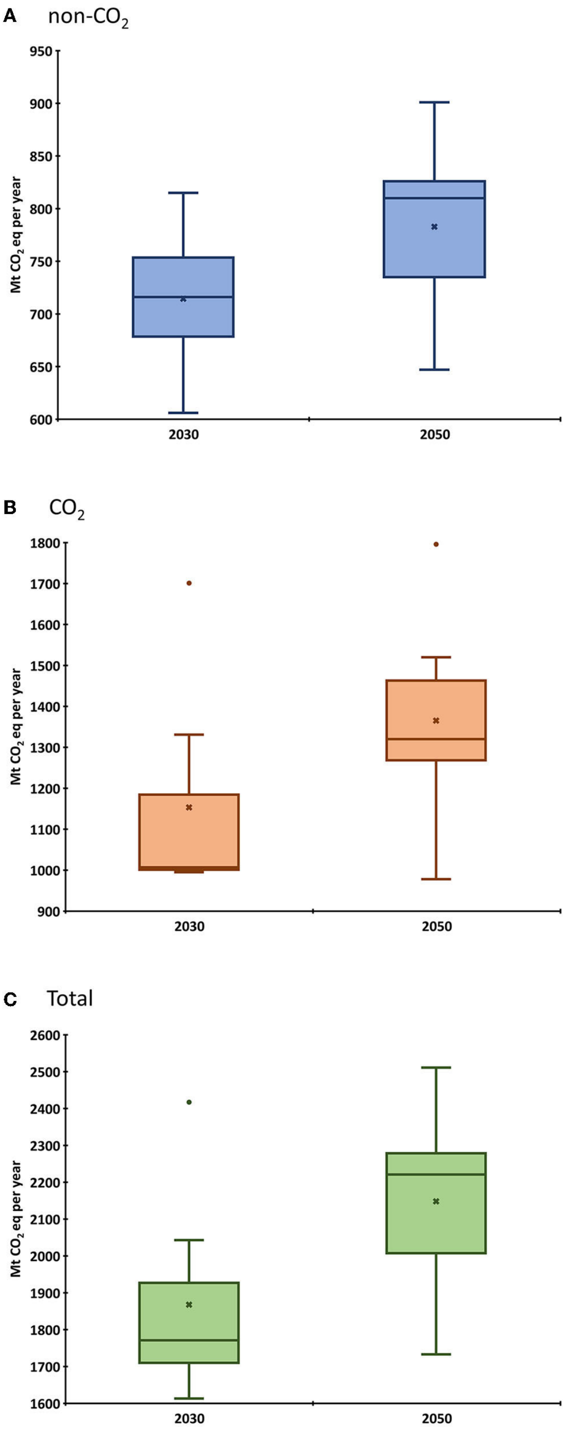


FIGURE 3
Global agriculture sector technical mitigation potential for **(A)** non-CO_2, **(B)** CO_2 and **(C)** Total for 2030 and 2050, at a carbon price of USD 70 per tCO_2eq. In these box-and-whisker diagrams, the box shows the upper and lower quartiles of the distribution of the results, and the 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 "x" within the boxes and the medians are shown as horizontal lines in the boxes. Source: IMPACT model.

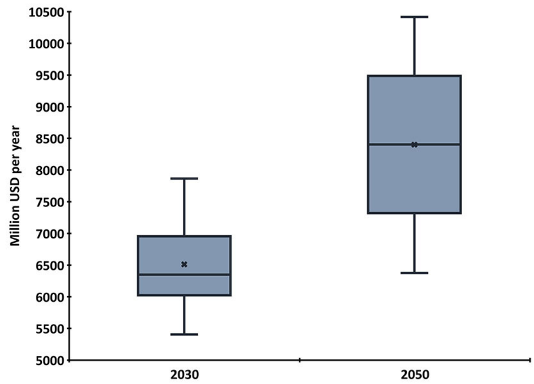


FIGURE 4
Global cost of technical mitigation, 2030 and 2050, million USD per year, at a carbon price of USD 70 per tCO_2eq. Source: Author estimates based on parameters derived from the literature.

innovation area, Dalberg finds 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 for 2015–2030. 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 have higher estimates of investment gaps to end hunger. 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

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

Technical mitigation options	$MtCO_2eq$/year	
	2030	2050
Cropland management	919	1,152
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	1,868	2,148

Source: Estimation by authors.
Values are relative to no adoption of these technical options.

with the estimate in this article indicates that investment in innovation may have especially high impacts on ending hunger while also improving the performance of climate change mitigation. Careful targeting of interventions to the hunger goal can also reduce the cost relative to the impact. The study of Laborde et al. (2016) has a relatively low-cost estimate for ending hunger by 2030, at USD 11 billion annually, arrived 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.

Model and analysis limitations

In common with the studies cited above, our analysis relies on many assumptions and estimated agricultural and economic relationships. As a global economic-biophysical model, IMPACT relies primarily on aggregate national statistics, together with sub-national down-scaling of climate and water resources and must therefore represent economic behavior in a relatively aggregated approach (Mason-D'Croz et al., 2019). The linkage of a disaggregated agricultural partial equilibrium model like IMPACT with GLOBE advances the assessment of economy-wide impacts of investments with feedback to agricultural incomes. 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. In this analysis, hunger is defined as the SDG 2.1 calorie-based target to end hunger. Future work should also focus on dietary and nutritional security and quality.

The study focuses on SDG 2 and the Paris Agreement pathways. Many other SDGs are also important, such as water resources and biodiversity. Future work on the policies and potentials to improve performance in meeting additional SDGs would be valuable but are beyond the scope of the current analysis.

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 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 a 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. (2021a), broader malnutrition problems, together with the continued transformation of food systems in developing countries, require wider-ranging approaches and interventions to improve 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 into account 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).

Weak governance, fragile states, extreme climate events, and conflict can reduce the potential gains from investment in agricultural R&D (Mason-D'Croz et al., 2019). The SSPs focus their narratives on long-running trends in the global economy, which, although 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 and extreme climate shocks, result in year-to-year variability and alter trajectories, at least in the short run. 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).

TABLE 10 Summary of total investment gap estimates to meet global goals from other studies.

Study	Goals	Estimate (USD)	Investments considered
ZEF and FAO (2020)	End hunger by 2030	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, and fertilizer use efficiency
FAO et al. (2015)	Adequate income and resources for all to access food by 2030	265 billion	Social protection, pro-poor rural investment, and public and private investment in productive sectors
Laborde et al. (2016)	End hunger by 2030	11 billion	Social safety nets, farm support to raise production and incomes, and 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	33 billion	Social protection, farmers' institutions, vocational training, farm inputs, R&D, improved feed, irrigation infrastructure, reduction of post-harvest losses, and support to small- and medium-sized enterprises
Baldos et al. (2020)	Offset yield losses projected by climate and crop models to 2050	187–1,384 billion	R&D for climate adaptation
Rosegrant et al. (2017)	Increase agricultural productivity and nearly end hunger by 2030	52 billion	R&D, resource management, and infrastructure (irrigation and rural roads)

The focus of our GHG emissions analysis is on emissions in agriculture consistent with a 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, emissions from transportation, downstream processing of food, the manufacture of tractors and fertilizer, expansion of solar power use in agriculture, or other relevant inputs. Emissions from these sources are included by IPCC guidelines in other, non-agricultural sectors such as transport and energy (Mbow et al., 2019). 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 article.

Analysis of potential food security improvements and GHG emissions reductions from improvement in agricultural value chains would be a particularly important extension of this analysis. Innovations and investments in the value chain would improve the prospects for meeting the SDG2 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, reduce marketing margins and post-harvest losses of food, thereby generating production and income gains and potentially significantly reducing hunger and reducing GHG emissions (Rosegrant et al., 2021a). 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. Expanded investments in these items will likely require partnerships with the private sector. Aggregating mechanisms could 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 support microfinance services (Otsuka et al., 2016). 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. 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, 2018). 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 (Aker et al., 2016).

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 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, regulatory and legal issues, farmer risk aversion, and market failures (Beach et al., 2015). Giller et al. (2009), for example, point to farm-level constraints to the adoption of conservation tillage for soil sequestration in Africa. These can include lower yields in some cases, increased labor and fertilizer requirements when herbicides are not used, limited access to external inputs, and a lack of mulch due to both low productivity and the priority given to feeding livestock with crop residues.

Constraints can also arise in the implementation of carbon sequestration programs (Pannell, 2021). With successful soil sequestration, soil carbon increases to a new equilibrium level after about 20–30 years and then stops. However, the soil sequestration methods need to be continued to avoid releasing the sequestered carbon. Costs continue without new benefits. Sequestration programs also need to ensure additionality, so that management options are additional to what farmers would do anyway. Monitoring and measuring soil carbon stored in soils is expensive, requiring regular soil testing to determine that carbon has been sequestered (Pannell, 2021). Measurement is costlier when it needs to be done for multiple small farms. Innovations in measurement through advances in information and communications technologies, including less-expensive soil testing 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.

Conclusion

This article 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. Another USD 6.5 billion per year, invested in technical climate-smart options, can achieve 2030 GHG emission reductions consistent with the Paris Agreement 2°C and 1.5°C pathways. Therefore, the estimated innovation investment gap to reduce hunger to 5% globally and reduce GHG emissions to a level consistent with the Paris pathways is USD 10.5 billion annually.

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. These investments in SSA, however, fail to achieve the SDG2.1 target by 2030 where the share at risk of hunger is still projected to be nearly 12%, though this is an important improvement over baseline levels.

The agricultural productivity growth generated, along with the adoption of technical mitigation options, achieves non-CO_2 GHG emissions savings of 1,010 $MtCO_2eq$/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 $MtCO_2eq$/year in 2030—far higher than the estimated 100 $MtCO_2eq$/year needed to support a 2°C climate trajectory. These investments do not achieve zero land-use change from agriculture but do reduce the rate of deforestation by an average of 925,000 ha/year by 2030.

Along with achieving global goals, the investment scenarios generate large economic returns. The R&D investment 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. The highest agricultural R&D investment scenario 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 GHG 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 include improved 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 are 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.

Data availability statement

Modeling assumptions and inputs are available at https://github.com/IFPRI/IMPACT. All other data necessary for this analysis are presented directly in the article.

Author contributions

MR conceived the approach to the research and led all aspects. TS and KW contributed to the modeling efforts and write-up of the manuscript. All authors have approved the final manuscript.

Funding

The research was co-financed by the UK's Foreign, Commonwealth & Development Office (FCDO) and CoSAI. This research was also supported by Funders contributing to the CGIAR Trust Fund (https://www.cgiar.org/funders/). The Commission on Sustainable Agriculture Intensification (CoSAI) was initiated and is supported by the CGIAR Research Program on Water, Land and Ecosystems (WLE), funded by the CGIAR Trust Fund and other donors. CoSAI Commissioners are independent. CoSAI is facilitated by a Secretariat based at the International Water Management Institute (IWMI) headquarters in Colombo, Sri Lanka.

Acknowledgments

This article is based on a working paper (Rosegrant et al., 2021b) hosted on the CoSAI website and https://cgspace.cgiar.org/. The research was guided by an Oversight Group, chaired by Donald Menzies (FCDO) and involving Rachel Lambert, Anna De Palma, both from FCDO; Julia Compton, Ruben Echeverria, Rodomiro Octavio, Uma Lele and Vara Prasad, all from CoSAI; Dhanush Dinesh from CCAFS; and Jim Jones, from the University of Florida. Study management and administration were provided by David Shearer and Josefina Achaval-Torre from the CoSAI Secretariat.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aker, J. C., Ghosh, I., and Burrell, J. (2016). "The promise (and pitfalls) of ICT for agriculture initiatives." *Agric. Econ.* 47, 35–48. doi: 10.1111/agec.12301

Alston, J. M., Andersen, M. A., James, J. S., and Pardey, P. G. (2011). The economic returns to U.S. public agricultural research. *Am. J. Agric. Econ.* 93, 1257–1277. doi: 10.1093/ajae/aar044

Baldos, U. L. C., Fuglie, K. O., and Hertel, T. W. (2020). The research cost of adapting agriculture to climate change: a global analysis to 2050. *Agric. Econ.* 51, 207–220. doi: 10.1111/agec.12550

Beach, R. H., Creason, J., Ohrel, S. B., Ragnauth, S., Ogle, S., Li, C., et al. (2015). Global mitigation potential and costs of reducing agricultural non-CO_2 greenhouse gas emissions through 2030. *J. Integr. Environ. Sci.* 12, 87–105. doi: 10.1080/1943815X.2015.1110183

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., et al. (2013). The Norwegian earth system model, NorESM1-M – part 1: description and basic evaluation of the physical climate. *Geosci. Model Dev.* 6, 687–720. doi: 10.5194/gmd-6-687-2013

Brown, S., Sathaye, J., Cannell, M., and Kauppi, P. E. (1996). Mitigation of carbon emissions to the atmosphere by forest management. *Commonw. For. Rev.* 75, 80–91.

Caballero, B. (2007). The global epidemic of obesity: an overview. *Epidemiol. Rev.* 29, 15. doi: 10.1093/epirev/mxm012

CGIAR (2022). *CGIAR Funding*. Available online at: https://www.cgiar.org/funders/ (accessed May 15, 2022).

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F., and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food* 2, 198–209. doi: 10.1038/s43016-021-00225-9

Dalberg (2021). *Investment Landscape for Transforming Agricultural Innovation Systems for People, Nature and Climate*. Hong Kong, China: Dalberg.

Del Grosso, S. J., and Cavigelli, M. J. (2012). Climate stabilization wedges revisited: can agricultural production and greenhouse gas reduction goals be accomplished? *Front. Ecol. Environ.* 10, 571–578. doi: 10.1890/120058

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., et al. (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Clim. Dyn.* 40, 2123–2165. doi: 10.1007/s00382-012-1636-1

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E., et al. (2012). GFDL's ESM2 global coupled climate-carbon earth system models. Part I: physical formulation and baseline simulation characteristics. *J. Clim.* 25, 6646–6665. doi: 10.1175/JCLI-D-11-00560.1

EPA (2019). *Global Non-CO2 Greenhouse Gas Emission Projections and Mitigation 2015–2030*. Washington, DC, United States: United States Environmental Protection Agency (EPA).

Evenson, R. E., and Gollin, D. (2003). Assessing the impact of the Green Revolution, 1960 to 2000. *Science* 300, 758–762. doi: 10.1126/science.1078710

Falck Zepeda, J., Yorobe Jr, J., Amir Husin, B., Manalo, A., Lokollo, E., Ramon G., et al. (2012). Estimates and implications of the costs of compliance with biosafety regulations in developing countries. *GM Crops and Food: Biotechnology in Agriculture and the Food Chain* 1, 1–8 doi: 10.4161/gmcr.18727

Fan, S., Headey, D., Laborde, D., Mason-D'Croz, D., Rue, C., Sulser, T. B., et al. (2018). *Quantifying the Cost and Benefits of Ending Hunger and Undernutrition: Examining the Differences among Alternative Approaches*. Washington, DC, United States: IFPRI.

Fan, S., Yosef, S., and Pandya-Lorch, R. (2019). "The way forward for nutrition-driven agriculture," in *Agriculture for Improved Nutrition: Seizing the Momentum*, eds S. Fan, S. Yosef, and R. Pandya-Lorch (Wallingford, United Kingdom: IFPRI and CABI), 209–214. doi: 10.1079/9781786399311.0209

FAO (2008). *FAO Methodology for the Measurement of Food Deprivation: Updating the Minimum Dietary Energy Requirements*. Rome, Italy: FAO Statistics Division.

FAO (2020). *Global Forest Resources Assessment 2020: Main Report* (accessed July 30, 2021).

FAO (2021a). *FAOSTAT Database of Greenhouse Gas Emissions From Agriculture*. Available online at: http://www.fao.org/faostat/en/#data/GT (accessed July 7, 2021).

FAO (2021b). *FAOSTAT Food Security Database*. Available online at: http://www.fao.org/faostat/en/#data/FS (accessed July 10, 2021).

FAO, International Fund for Agricultural Development (IFAD), and World Food Programme (WFP) (2015). *Achieving Zero Hunger: The Critical Role of Investments in Social Protection and Agriculture*. Rome, Italy: FAO.

Fischer, G., Shah, M., Tubiello, F. N., and van Velhuizen, H. (2005). Socio-economic and climate change impacts on agriculture: an integrated assessment. *Philos. Trans. Royal Soc. B* 360, 2067–2083. doi: 10.1098/rstb.2005.1744

Frank, S., Beach, R., Havlík, P., Valin, H., Herrero, M., Mosnier, A., et al. (2018). Structural change as a key component for agricultural non-CO_2 mitigation efforts. *Nat. Commun.* 9, 1060. doi: 10.1038/s41467-018-03489-1

Fuglie, K. (2016). The growing role of the private sector in agricultural research and development world-wide. *Glob. Food Sec.* 10, 29–38. doi: 10.1016/j.gfs.2016.07.005

Giller, K. E., Witter, E., Corbeels, M., and Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Res.* 114, 23–34. doi: 10.1016/j.fcr.2009.06.017

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., et al. (2010). Food security: the challenge of feeding 9 billion people. *Science* 327, 812–818. doi: 10.1126/science.1185383

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M. C., et al. (2014). Climate change mitigation through livestock system transitions. *Proc. Natl. Acad. Sci. USA.* 111, 3709–3714. doi: 10.1073/pnas.1308044111

Hawkes, C., Harris, J., and Gillespie, S. (2017). "Changing diets: urbanization and the nutrition transition," in *2017 Global Food Policy Report*, eds S. Fan, J. Falik, R. Pandya-Lorch, K. Park, P. Stedman-Edwards, K. von Grebmer, S. Yosef, and L. Zseleczky (Washington, DC, United States: IFPRI), 34–41.

Herrero, M., Henderson, B., Havlík, P., Thornton, P. K., Conant, R. T., Smith, P., et al. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nat. Clim. Chang.* 6, 452–461. doi: 10.1038/nclimate2925

IPCC (2006). "Emissions from livestock and manure management," in *2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry, And Other Land Use,* eds S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (Cambridge, United Kingdom: Cambridge University Press), Chapter 10.

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC).

IPCC (2018). "Summary for policymakers," in: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Geneva, Switzerland: IPCC).

Iversen, T., Bentsen, M., Bethke, I., Debernard, J. B., Kirkevåg, A., Seland, Ø., et al. (2013). The Norwegian earth system model, NorESM1-M – Part 2: Climate response and scenario projections. *Geosci. Model Dev.* 6, 389–415. doi: 10.5194/gmd-6-389-2013

Jones, C. D., Hughes, J. K., Bellouin, N., Hardiman, S. C., Jones, G. S., Knight, J., et al. (2011). The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geosci. Model Dev.* 4, 543–570. doi: 10.5194/gmd-4-543-2011

Jones, J., Hoogenboom, G., Porter, C., Boote, K., Batchelor, W., Hunt, L., et al. (2003). The DSSAT Cropping System Model. *Eur. J. Agron.* 18, 235–265. doi: 10.1016/S1161-0301(02)00107-7

Kearney, J. (2010). Food consumption trends and drivers. *Philos. Trans. Royal Soc. B Biol. Sci.* 365, 2793–2807. doi: 10.1098/rstb.2010.0149

Kissinger, G., Herold, M., and De Sy, V. (2012). *Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers*. Vancouver, Canada: Lexeme Consulting.

Laborde, D., Bizikova, L., Lallemant, T., and Smaller, C. (2016). *Ending Hunger: What Would It Cost?* Winnipeg, Canada: International Institute for Sustainable Development (IISD).

Laborde, D., Parent, M., and Smaller, C. (2020). *Ending Hunger, Increasing Incomes, and Protecting the Climate: What would it cost donors?* Winnipeg, Canada: IISD and IFPRI.

Lenaerts, B., de Mey, Y., and Demont, M. (2018). Global impact of accelerated plant breeding: evidence from a meta-analysis on rice breeding. *PLoS ONE* 13, e0199016. doi: 10.1371/journal.pone.0199016

Mason-D'Croz, D., Sulser, T. B., Wiebe, K., Rosegrant, M. W., Lowder, S. K., Nin-Pratt, A., et al. (2019). Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger. *World Dev.* 116, 38–53. doi: 10.1016/j.worlddev.2018.12.006

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., et al. (2019). "Food security," in *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, eds. P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley (Geneva, Switzerland: IPCC), Chapter 5.

McKinsey and Company (2020). *Agriculture and Climate Change: Reducing Emissions Through Improved Farming Practices*. New York, United States: McKinsey and Company.

Nelson, G. C., Rosegrant, M. W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., et al. (2010). *Food Security, Farming, and Climate Change to 2050*. Washington, DC, United States: IFPRI. Available online at: http://www.ifpri.org/sites/default/files/publications/rr172.pdf

Nin-Pratt, A. (2016). "Inputs, productivity and agricultural growth in sub-Saharan Africa," in *Productivity and Efficiency Analysis*, eds W. H. Greene, L. Khalaf, R. C. Sickles, M. Veall, and M. C. Voia (Berlin, Germany: Springer), 175–201. doi: 10.1007/978-3-319-23228-7_11

Nin-Pratt, A., Falconir, C., Ludena, C., and Martel, P. (2015). *Productivity and the Performance of Agriculture in Latin America and the Caribbean: From the Lost Decade to the Commodity Boom*. Washington, DC, United States: Inter-American Development Bank (IDB). Available online at: http://cdm15738.contentdm.oclc.org/cdm/ref/collection/p15738coll5/id/5105

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., et al. (2015). The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.* 42, 169–180. doi: 10.1016/j.gloenvcha.2015.01.004

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., et al. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Chang.* 122, 387–400. doi: 10.1007/s10584-013-0905-2

Otsuka, K., Nakano, Y., and Takahashi, K. (2016). "Contract farming in developed and developing countries." *Ann. Rev. Res. Econ.* 8, 353–376. doi: 10.1146/annurev-resource-100815-095459

Pannell, D. (2021). *Soil Carbon is a Highly Flawed Climate Policy, Parts 1–3*. Available online at: https://www.pannelldiscussions.net/2021/04/346-soil-carbon-1/ (accessed on July 30, 2021).

Pardey, P., Beintema, N., Steven, D., and Wood, S. (2006). *Agricultural Research: A Growing Global Divide?* Washington, DC, United States: IFPRI.

Pourkheirandish, M., Golicz, A. A., Bhalla, P., and Singh, M. B. (2020). Global role of crop genomics in the face of climate change. *Front. Plant Sci.* 11, 922. doi: 10.3389/fpls.2020.00922

Prager, S. D., and Wiebe, K. (2021). Strategic foresight for agriculture: past ghosts, present challenges, and future opportunities. *Glob. Food Secur.* 28, 100489. doi: 10.1016/j.gfs.2020.100489

Reisinger, A., Havlík, P., Riahi, K., van Vliet, O., Obersteiner, M., and Herrero, M. (2013). Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. *Clim. Chang.* 117, 677–690. doi: 10.1007/s10584-012-0593-3

Robinson, S., Mason-D'Croz, D., Islam, S., Sulser, T. B., Robertson, R., Zhu, T., et al. (2015). *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description, Version 3*. Washington, DC: IFPRI. Available online at: http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825 doi: 10.2139/ssrn.2741234

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018). "Mitigation pathways compatible with 1.5°C in the context of sustainable development," in *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. (Geneva, Switzerland: IPCC), 93–174.

Rosegrant, M. W., Fan, S., and Otsuka, K. (2021a). "Global issues in agricultural development," in *Agricultural Development: New Perspectives in a Changing World*, eds K. Otsuka, and S. Fan (Washington, DC, United States: IFPRI), 35–78. doi: 10.2499/9780896293830_02

Rosegrant, M. W., Sulser, T. B., Dunston, S., Cenacchi, N., Wiebe, K., and Willenbockel, D. (2021b). *Estimating the Global Investment Gap in Research and Innovation for Sustainable Agriculture Intensification in the Global South*. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification, 75.

Rosegrant, M. W., Sulser, T. B., Mason-D'Croz, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., et al. (2017). *Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio*. Washington DC, United States: IFPRI. Available online at: https://www.ifpri.org/publication/foresight-modeling-agricultural-research

Ruel, M. T., Garrett, J. L., and Yosef, S. (2017). "Food security and nutrition: growing cities, new challenges," in *2017 Global Food Policy Report*, eds S. Fan, J. Falik, R. Pandya-Lorch, K. Park, P. Stedman-Edwards, K. von Grebmer, S. Yosef, and L. Zseleczky (Washington, DC, United States: IFPRI), 24–33.

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D. M., Schüngel, J., et al. (2011). An integrated approach to modelling land-use change on continental and global scales. *Environ. Model. Softw.* 26, 1041–1051. doi: 10.1016/j.envsoft.2011.02.013

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., et al. (2014). "Agriculture, forestry and other land use (AFOLU)," in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J. C. Minx (Cambridge, United Kingdom: Cambridge University Press), 811–922.

Smith, P., Haberl, H., Popp, A., Erb, K.-H., Lauk, C., Harper, R., et al. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Chang. Biol.* 19, 2285–2302. doi: 10.1111/gcb.12160

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., et al. (2007). "Agriculture," in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer (New York, United States: Cambridge University Press), 498–540.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., et al. (2008). Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. *Agric. Ecosyst. Environ.* 118, 6–28. doi: 10.1016/j.agee.2006.06.006

Smith, P., Nkem, J., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., et al. (2018). *Chapter 6: Interlinkages between Desertification, Land Degradation, Food Security and GHG Fluxes: Synergies, Trade-offs and Integrated Response Options. In: Special Report on Climate Change and Land*. Geneva, Switzerland: IPCC.

Sulser, T. B., Wiebe, K. D., Dunston, S., Cenacchi, N., Nin-Pratt, A., Mason-D'Croz, D., et al. (2021). *Climate Change and Hunger: Estimating Costs of Adaptation in the Agrifood System*. Washington, DC, United States: IFPRI. doi: 10.2499/9780896294165

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, 1554. doi: 10.1098/rstb.2010.0134

UNFCCC (2020). *The Paris Agreement*. Available online at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed May 15, 2022).

USAID. (2018). *Digital Farmer Profiles: Reimagining Smallholder Agriculture*. Washington, DC: United States Agency for International Development (USAID).

van Ittersum, M., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., and Hochman, Z. (2013). Yield gap analysis with local to global relevance—a Review. *Field Crops Res.* 143, 4–17. doi: 10.1016/j.fcr.2012.09.009

van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., et al. (2011). RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Clim. Chang.* 109, 95–116. doi: 10.1007/s10584-011-0152-3

Waltz, E. (2018). With a free pass, CRISPR-edited plants reach market in record time. *Nat. Biotechnol.* 36, 6–7. doi: 10.1038/nbt0118-6b

Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H., et al. (2011). MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. *Geosci. Model Dev.* 4, 845–872. doi: 10.5194/gmd-4-845-2011

Willenbockel, D., Robinson, S., Mason-D'Croz, D., Rosegrant, M. W., Sulser, T. D. S., and Cenacchi, N. (2018). *Dynamic Computable General Equilibrium Simulations in Support of Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio: Linking the IMPACT and GLOBE Models*. Washington, DC, United States: IFPRI. Available online at: http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/132757

Wise, M., Calvin, K., Kyle, P., Luckow, P., and Edmonds, J. (2014). Economic and physical modeling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. *Clim. Chang. Econ.* 5, 145003. doi: 10.1142/S2010007814500031

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F. N., et al. (2016). Reducing emissions from agriculture to meet the 2°C target. *Glob. Chang. Biol.* 22, 3859–3864. doi: 10.1111/gcb.13340

World Bank (2012). *Managing Risk, Promoting Growth: Developing Systems for Social Protection in Africa. In the World Bank's Africa Social Protection Strategy 2012-2022*. Washington, DC, United States: World Bank, 103.

Yan, X., Akiyama, H., Yagi, K., and Akimoto, H. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Glob. Biogeochem. Cyc.* 23, GB2002. doi: 10.1029/2008GB003299

ZEF and FAO (2020). *Investment Costs and Policy Action Opportunities for Reaching a World Without Hunger (SDG 2)*. Bonn, Germany: ZEF (Center for Development Research).

Zhu, H., Li, C., and Gao, C. (2020). Applications of CRISPR–Cas in agriculture and plant biotechnology. *Nat. Rev. Mol. Cell Biol.* 21, 661–677. doi: 10.1038/s41580-020-00288-9

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 03 November 2022
DOI 10.3389/fsufs.2022.1031562

Check for updates

OPEN ACCESS

EDITED BY
Julia Compton,
Independent Researcher, Cardiff, United Kingdom

REVIEWED BY
Mywish Maredia,
Michigan State University, United States
Paul Heisey,
United States Department of Agriculture (USDA), United States

*CORRESPONDENCE
Keith Fuglie
keith.fuglie@usda.gov

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 30 August 2022
ACCEPTED 17 October 2022
PUBLISHED 03 November 2022

CITATION
Fuglie K, Wiebe K, Sulser TB, Cenacchi N and Willenbockel D (2022) Multidimensional impacts from international agricultural research: Implications for research priorities. *Front. Sustain. Food Syst.* 6:1031562. doi: 10.3389/fsufs.2022.1031562

Multidimensional impacts from international agricultural research: Implications for research priorities

Keith Fuglie[1]*, Keith Wiebe[2], Timothy B. Sulser[2], Nicola Cenacchi[2] and Dirk Willenbockel[3]

[1]U.S. Department of Agriculture, Economic Research Service, Washington, DC, United States, [2]International Food Policy Research Institute (IFPRI), Washington, DC, United States, [3]Institute of Development Studies, Brighton, United Kingdom

Investors in international agricultural research seek sustainable agri-food technologies that can potentially serve multiple objectives, including economic growth, food security, and sustainable use of natural resources. We employ quantitative economic models to examine the potential multi-dimensional impacts of agricultural productivity gains in the Global South. These models take into account behavior responses to agricultural technological change, i.e., how productivity changes may affect decisions on what to produce, trade, and consume. We compare potential impacts of productivity growth in different commodities and regions and assess implications along several impact dimensions, including economic and income growth, the population at risk of hunger, adequacy of protein and micronutrients in human diets, land and water use, and greenhouse gas emissions. Potential impacts vary widely by commodity group and by region. These results reveal strengths and potential tradeoffs of different R&D spending allocations, and can help inform decision-making about an optimal R&D portfolio that takes into account the multiple objectives of agricultural investments.

KEYWORDS

agricultural productivity, CGIAR, impact assessment, parity model, IMPACT model, research and development (R&D)

Introduction

Research investments in agriculture are a primary driver of productivity improvement and contribute significantly to the Millennium Development Goals (MDGs) of reducing poverty, eliminating hunger, and the sustainable use of natural resources. In the Global South, national governments are the primary investors in agricultural research and development (R&D), followed by the private sector and the CGIAR system of international agricultural research centers (Pardey et al., 2016). And while economic studies have found that on average, returns to investment in agricultural research have been high, there is also a wide range in the estimated rates of return across research programs and projects (Alston et al., 2000; Hurley et al., 2018). Since the impacts of the most successful agricultural research investments are large, misallocation of R&D resources to low impact programs or projects carries a high opportunity cost. However, predicting the future impacts of current research investments is highly uncertain. Moreover, the governments, donors and other stakeholders who fund and support agricultural research are usually concerned with more than just maximizing economic returns. They often have multiple objectives for their funding contributions—including equity, food security, nutrition, and environmental sustainability. Nonetheless, any R&D portfolio allocation requires making judgements, however uncertain and ill-informed, about how it will advance these objectives (Ruttan, 1982).

This paper provides a quantitative analysis of the potential impacts of a commodity-oriented R&D portfolio designed to raise the productivity of agricultural systems in the Global South. Commodity-oriented R&D occupies about 65% of the R&D personnel in these national agricultural research systems (ASTI, 2022), nearly 40% of global private spending on food and agricultural R&D (Fuglie, 2016), and about one-third of annual expenditures by the CGIAR (Alston et al., 2020). This analysis can assist in allocating investments in international and national agricultural research by identifying the commodities and production systems where productivity improvements have the greatest potential to advance societal welfare. Using quantitative modeling, the paper describes the potential impacts of commodity- and region-specific productivity growth on incomes, food security, nutrition, land and water use, and greenhouse gas (GHG) emissions from agriculture.

This quantitative analysis is based on simulations from a model of the global agri-food economy to project impacts of agricultural productivity growth out to 2030. It extends Wiebe et al. (2021), which focused on 20 food crops, to a broader set of crop and livestock commodities. Model simulations examine how changes in agricultural productivity might affect output, resource use, and prices, and take into account how producers and consumers respond to these changes. It provides quantitative assessments of how agricultural productivity growth in various commodities could impact incomes, poverty, undernutrition and natural resource use in developing countries in the coming decade. Applying the "parity rule" to these results—in which R&D is allocated among commodities or regions in proportion to anticipated benefits—suggests a way to move toward an efficient R&D portfolio, or one that achieves the greatest impact on desired outcomes given available funding for R&D. The results show that there are likely to be trade-offs among the multiple objectives for international agricultural R&D. Accelerating productivity growth (and R&D investment) in some commodities will likely have stronger effects on some objectives, like income growth, while productivity growth in other commodities may have stronger effects on other objectives, such as reducing hunger, saving land and water resource use or curbing greenhouse gas emissions from agriculture. Policy makers may need to balance R&D allocation decisions among these competing objectives or rely on other policy instruments to address them. Alston et al. (1995), for example, argue that an R&D reallocation that sacrifices economic growth to achieve more equity (or some other socially desirable objective) may not be efficient if other policy instruments can more effectively address the equity concern. The World Resources Institute (2019), for example, lays out a menu of policy options -including but not limited to raising agricultural productivity—that are likely to be needed to meet MDGs. In a recent paper, Fuglie et al. (2022a) show that while accelerating agricultural productivity growth in developing countries is likely to reduce land use change and greenhouse gas emissions, it would work better if done in conjunction with land policies that protected especially carbon-rich lands from conversion to agricultural uses. Similarly, food policies may be more effective than R&D investment in achieving nutritional goals for vulnerable populations (Gomez et al., 2013; Alston et al., 2016). Nonetheless, robust R&D spending that kept food prices low would likely reduce the cost of both environmental and food assistance interventions (Gomez et al., 2013; Fuglie et al., 2022a).

Materials and methods

As Ruttan (1982) noted, any research resource allocation process involves making judgements about two central questions: (1) What is the feasibility of developing technology or advancing knowledge if research resources are allocated to a particular commodity, resource, or problem area, and (2) What will be the value to society of the new technology or knowledge if the research is successful? The first question deals with the supply of technology with the second question focused on the demand for technology. While judgements about technical feasibility can best be answered by scientists working at the leading edge of these issues, informed answers about its demand and its potential societal impact and value require the use of formal economic analysis. The quantitative models and analysis in this paper provide information of particular relevance to the second question—the value of research if it successfully develops technologies and knowledge that are widely adopted.

One approach that has been used to allocate R&D resources across commodities is the parity model (Ruttan, 1982; Alston et al., 1995). According to the "parity rule," R&D is allocated among commodities in proportion to their market value. [1] Since the highest returns to agricultural research will likely

1 The parity model is sometimes referred to as the "congruence model" where the ratio between commodity value and commodity R&D expenditure is defined as the "congruence ratio." The parity rule is satisfied when congruence ratios are equated across commodities.

be for technologies that have wide potential use, it stands to reason that commodities, production systems, and problem areas with the largest economic significance should generally receive greater attention from (public or private) research and other investments. To reflect objectives other than economic growth, weighted-parity rules have sometimes been used. For example, Wiebe et al. (2021) and Fuglie et al. (2022b) weighted the value of commodities by the country-level prevalence of extreme poverty and child stunting to give greater weight to commodities important to countries with high measures of those attributes. These weighted commodity values were then used to derive weighted-parity rules to inform the allocation of resources in international agricultural research.

While the parity model is straightforward to apply, there are several reasons why it might not result in an efficient allocation of R&D resources. As Ruttan (1982) noted, differences in the technical feasibility of raising productivity across commodities are one reason. On the demand side, current market values of commodities may not fully reflect their social value, especially a decade or more into the future when today's R&D investments come to fruition through widespread technology adoption. For example, as per capita income rises in the Global South, consumer preferences are expected to diversify away from food staples to include more animal products, fruits, vegetables and processed foods. In addition, social and policy preferences value more than just maximizing economic or income growth. If some commodities use up relatively more (unpriced but scarce) environmental resources than others, market valuation may overstate their social value. Similarly, if policy makers have preferences for equity or hunger alleviation, and if some commodities are more important to low income or malnourished populations, then market values may understate their social values.[2]

This study uses the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to explore multiple dimensions of impact from raising productivity in different commodities and regions in the Global South. Specifically, the IMPACT model is used to derive estimates of how changes in agricultural productivity in the target regions could affect incomes, the population at risk of hunger, per capita nutrient availability for protein, iron and zinc, use of land and water, and GHG emissions from agriculture. Impacts will depend on the magnitude of a productivity change, where the change takes place, and which commodities are affected. Ultimately, we are interested in observing which agricultural R&D investments are more likely to lower hunger, improve income and favor environmental indicators, whether the same investment scenario may benefit all dimensions, and if not, which scenarios perform better for which indicators.

The IMPACT simulation model is a system of models based on a partial equilibrium, multimarket economic model of the global agricultural economy that simulates national and international agricultural markets. Because increases in agricultural productivity can lead to lower local and global commodity and food prices, it affects behavior and incomes of not only producers but also consumers. Moreover, productivity increases in one country or region can affect welfare in other regions through changes in prices and trade. The IMPACT model accounts for how farmers and households alter their decisions on what to produce and consume, and how commodities are utilized and traded as incomes and prices change. Links to climate models, water models, and crop models support the integrated study of changing environmental, biophysical, and socioeconomic trends, allowing for in-depth analysis of a variety of critical issues of interest to policymakers at national, regional, and global levels. More information can be found at https://www.ifpri.org/project/ifpri-impact-model, and from the main documentation of the model (Robinson et al., 2015).

The analysis focuses on R&D allocation among crop and livestock commodities important to 103 developing countries in the Global South, which we call the "target area" (Figure 1). The target area includes countries in Southeast Asia, South Asia, West and Central Asia (except for Kazakhstan and the high income countries of the Arabian peninsula), Africa, and part of Latin America (excluding Brazil and southern cone countries). These countries are divided into the six regions depicted in Figure 1. The target area encompasses most of the low and middle-income countries in tropical and sub-tropical zones except for China and Brazil, which, because of their strong national agricultural research programs, are less dependent on international agricultural research investments that focus on the Global South.

The simulation model forecasts global food demand using income and population changes in 2030 based on the IPCC[3] middle-of-the-road GDP and population scenario (SSP2) (O'Neill et al., 2014). In the baseline scenario, agricultural yields are held fixed at 2010 levels. The productivity investment scenarios then assume a 25% increase in productivity by 2030 and compare outcomes against the baseline scenario of no yield change. This rate of yield growth is comparable to what many commodities in this group of countries achieved over 2000–2019 (Table 1). Yield of cereal grains, for example, grew at an

2 One approach to R&D prioritization that explicitly takes into account both technology supply and demand is ex ante benefit-cost analysis. This approach requires identification and quantification of location-specific constraints to productivity by commodity and detailed assessments of the cost and likelihood of success of alternative potential technical solutions. For international agricultural research, benefit-cost analysis may be better suited for project selection within commodity and systems research programs. See Pemsl et al. (2022) for an example of the use of ex ante benefit-cost analysis for project prioritization within CGIAR root, tuber and banana research programs.

3 IPCC is the Intergovernmental Panel on Climate Change.

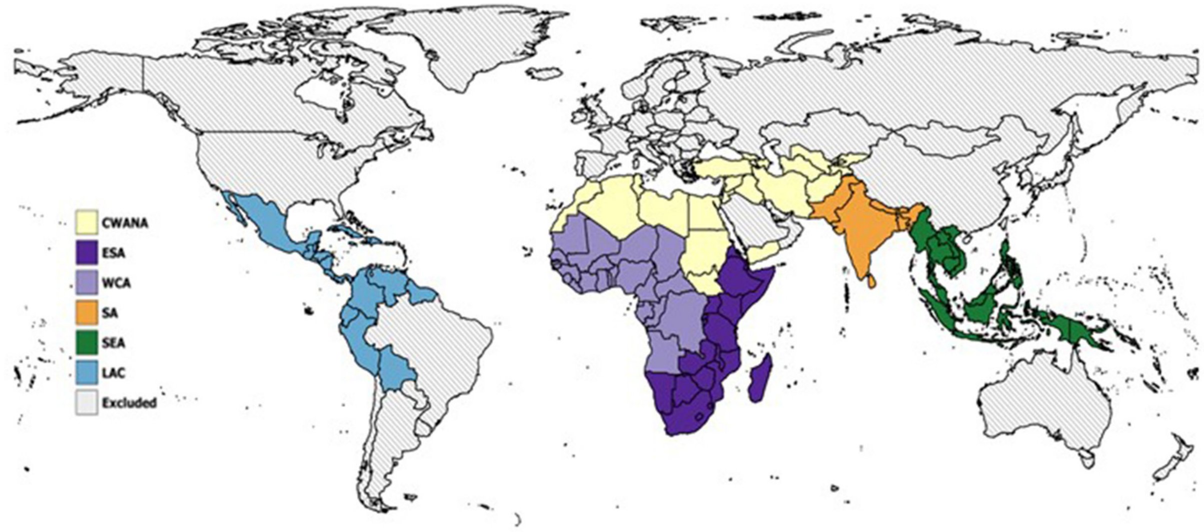


FIGURE 1
Global map showing countries and regions of interest. LAC, Latin America & Caribbean; CWANA, Central, West Asia & North Africa; WCA, Western & Central Africa; ESA, Eastern & Southern Africa; S Asia, South Asia; SE Asia, Southeast Asia & Pacific. The gray-hatched areas are excluded from the quantitative assessment but are part of the simulation framework as documented in Robinson et al. (2015). For some measures, ESA and WCA countries are grouped together into sub Saharan Africa (SSA).

average annual rate of 1.46% for a cumulative yield growth of 34% over these 20 years. In livestock, yield of beef cattle increased by 27% and dairy yield per cow increased by 45%, while yield improvement in small ruminant meat and milk was considerably lower.

A first set of scenarios focuses on increased productivity for different commodity groups; the second set simulates increased productivity across all commodities for different regions (Table 2). For example, for the Cereals crop productivity scenario we assume that R&D investments increase yields of cereal grains in the target area by 25% between 2010 and 2030. Yields for other commodities in the target area and yields for all crops in the rest of the world are held constant. Outcomes are compared against the baseline scenario of constant yield for all crops everywhere.[4] The goal is to isolate and compare the impact of accelerating productivity growth in particular commodity groups in the target countries. However, final, equilibrium yields may differ from the target levels due to endogenous effects within the model, mainly through price changes and shifts in trade as markets adjust to different scenario conditions.

4 Results for the baseline scenario (assuming no productivity growth between 2010 and 2030) are reported in Appendix Table A1. We do not report results of a scenario in which we shock productivity of all commodities worldwide, as our goal is not to predict world outcomes but rather to compare the relative impacts of raising productivity across commodities and developing regions. See Rosegrant et al. (2022) for an assessment of total agricultural R&D spending that may be needed to meet several MDG and climate goals for developing countries.

The regional productivity scenarios are built in the same general way: they explore the impact of targeting investments to each of the six CGIAR regions (CWANA, ESA, LAC, SA, SEA, WCA), one at a time. For each regional scenario, all the commodity groups in that region experience a 25% yield increase between 2010 and 2030, while yields for all commodities in all the other countries of the world are held constant.

While quantitative impacts are sensitive to the 25% yield growth assumption, the *relative* impacts across commodities and regions are not. Assuming a common productivity shock higher (lower) than 25% would raise (reduce) projected impacts, but the impacts would change by a similar scale across commodities and regions. Thus, results are robust for the purposes of comparing impacts of alternative R&D allocations among commodities and regions.

Measuring impact on economic or income growth

The IMPACT model is linked to the global dynamic computable general equilibrium model, GLOBE-Energy. The role of GLOBE within the framework of the project is to assess the macroeconomic income and welfare effects associated with the alternative scenarios (Willenbockel et al., 2018). GLOBE captures the multiplier effects of agricultural growth on the rest of the economy. Income in this modeling framework is represented by average annual gross domestic product (total and per capita). In practice, the outputs from a first run of

TABLE 1 Historical rates of commodity yield growth in the target countries.

Commodity	Value of production 2017–2019 (US$billion/ year)	Yield growth rate over 2000–2019 (%/year)	Total yield growth over 2000–2019 (%)
Cereal grains	312.4	1.46	34
Roots and tubers	124.6	0.58	12
Oilseeds and pulses	69.5	1.19	27
Vegetables	160.8	0.71	15
Fruit	157.8	1.12	25
Cotton	31.6	1.10	25
Coffee	14.1	0.76	16
Cattle meat	80.0	1.18	27
Dairy milk	102.5	1.84	45
Pig meat	26.7	1.23	28
Sheep and goat meat	42.0	−0.05	−1
Sheep and goat milk	10.1	0.60	13

Achieving a 25% increase in yield over 20 years requires an average annual growth rate of 1.12%.
Yield is total quantity produced divided by total hectares harvested or total animals in the 103 country target area. Meat yield is measured as quantity from slaughter per animal in stock; Milk and egg yield is measured as quantity per producing animal.
Source: derived from FAOSTAT.

the scenarios in IMPACT are used as input into GLOBE as shocks to total factor productivity. GLOBE then simulates the changes in GDP that may be expected when the productivity of agriculture increases, and the effects are transmitted to the wider economy. In turn, the changes in GDP act as exogenous input back into another iteration in IMPACT, thereby affecting agricultural production, demand, and ultimately food security.

Measuring impacts on the population at risk of hunger

Estimates of the population at risk of hunger are the main food security metric produced through IMPACT simulations. It is the share of a population consuming below a minimum caloric requirement. The estimation uses the FAO methodology (FAO, 2008), which is based on a strong empirical relationship between per capita food availability and the share of undernourished within a population. The methodology postulates a distribution of per capita caloric intake around the mean per capita caloric availability and integrates this density function up to the minimum caloric requirement. This gives the population share consuming below the minimum requirement. An increase in mean per capita caloric availability shifts the distribution and reduces the estimated share of the population consuming below the minimum requirement.

Measuring impacts on protein and micronutrient availability in human diets

Micronutrient modeling follows the nutrient accounting framework established in the IMPACT model described in Beach et al. (2019). The approach translates the GENuS database (Smith et al., 2016) into commodity-level nutrient content coefficients that represent average availability through per capita consumption. The core components of this accounting framework provide per capita nutrient availability at the country level (which can be aggregated up to larger geographies with population weights) and ratios of this availability to country-specific recommended nutrient intakes (RNI) across modeled scenarios. Data availability issues force a focus on protein, iron, and zinc, which are useful indicator nutrients to assess diets beyond simple calorie measures.

For this analysis, we extend the availability numbers from the Beach et al. (2019) approach into an additional metric intended to be more easily interpretable for policymaking. We used data and models established by Wessels and Brown (2012) to construct an estimate of the share of a country's population at risk of inadequate supply of dietary zinc[5]. The construction of zinc estimates in Wessels and Brown (2012) provides a consistent model of population level availability of dietary zinc compared to physiological requirements ("% [of] mean physiological requirement"), which is comparable to the RNI ratios from the Beach et al. (2019) approach. We estimate an elasticity (−0.84) of the relationship between the Wessels and Brown's (2012) "estimated % of population with inadequate zinc intake" with IMPACT's RNI ratio and use this to project the change in country level population at risk of inadequate dietary zinc intake.

Measuring impacts on land and water use

In IMPACT, cropland is estimated as harvested area, that is total area planted and harvested within a year (it may include multiple harvests on the same land in a year). The total land supply over time is driven by exogenous trends in the availability of area for agriculture, as well as endogenous responses to changes in area demand, which in IMPACT is a function of changes in commodity prices (Robinson et al., 2015). The exogenous trends in harvested area include changing land

5 We also investigated the potential for developing this metric based on inadequate iron intake. However, the complexities of interacting co-determinants for iron adequacy for different segments of the population make this a much more complicated model.

TABLE 2 Summary of productivity investment scenarios.

Scenarios	Targets (crops/regions)	Scenario description	Scenario names
Commodity productivity scenarios	Cereal grains	Increase yield in one commodity group in target countries by 25% over 2010 level, while holding yields of other commodity groups and in non-target countries unchanged	Cereals+
	Oil crops		Oilcrops+
	Pulses		Pulses+
	Roots and tubers		RT+
	Fruit and vegetables		FV+
	Smallholder cash crops		Cash Crops+
	Livestock		Livestock+
Regional productivity scenarios	Central, West Asia & N Africa	Increase yield in all commodity groups in a region by 25% over 2010 levels, while holding yields in other regions unchanged	CWANA+
	East & Southern Africa		ESA+
	Latin American countries		LAC+
	South Asia		SASIA+
	SE Asia		SEASIA+
	West & Central Africa		WCA+
Reference scenario	Baseline with zero yield growth	No productivity changes over 2010 level	REF

use intensity that allows for multicropping. The scenarios of increasing productivity used in this analysis are focused on yield per hectare (or animal) per year.

Estimates of water use rely on the communication between the core IMPACT multimarket model, the IMPACT water basin simulation model (IWSM), and the crop water allocation and stress (ICWASM) model (Robinson et al., 2015). Briefly, a global hydrology model (IGHM) simulates rainfall, evapotranspiration and runoff in each basin. These hydrologic outputs are fed into IWSM, which manages water basin storage, and optimizes irrigation water distribution in a watershed. The information on irrigated water supply enters ICWASM, and the model provides the IMPACT multimarket model with water stress-induced crop yield reductions for both irrigated and rainfed crops. In these steps, the model keeps track of the blue and green water use across rainfed and irrigated systems.

Measuring impacts on greenhouse gas emissions

The focus of this analysis is on direct on-farm agricultural emissions and emissions from land use change and the ensuing loss of carbon storage in soils and forests. All emissions estimates are converted to CO_2 equivalents by multiplying the amount of GHG by the respective global warming potential.

For each scenario, we estimate CO_2 emissions from loss of forested area due to the expansion of cropland, methane emissions (CH_4) from rice cultivation and enteric emissions from livestock, and emissions of nitrous oxide (N_2O) from the application of manure and synthetic fertilizer to cropland. The results are reported in terms of change from the baseline scenario. The calculations are based on the methodology developed by Rosegrant et al. (2017). We provide some description of the process below and refer to the methodology sections of these two references for additional details.

Emissions are estimated by post-processing the outputs of the IMPACT model. To estimate N_2O emissions we used the IPCC Tier 1 default factors for direct N_2O 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) (IPCC, 2006; Yan et al., 2009). These factors were multiplied by the N fertilizer consumption projected in IMPACT for each country and each crop/commodity (see Appendices F and H in Rosegrant et al., 2017). It is important to note that our estimates exclude the indirect N_2O emissions from nitrogen leaching and runoff, and from atmospheric nitrogen deposition.

Estimates of CH_4 emissions from rice cultivation derive from the combination of IPCC Tier 1 and 2 emission factors (as in Yan et al., 2009), with the crop yields projected by IMPACT. The CH_4 emissions from rice production are first calculated for a unit of area and then multiplied by the rice production areas projected by IMPACT.

To estimate CH_4 emissions from ruminants we multiplied the animal numbers projected in IMPACT (both slaughtered cattle and dairy animals) by the per-head emission value obtained from the enteric fermentation section of FAOSTAT (see also Appendix F in Rosegrant et al., 2017).

Finally, CO_2 emissions were estimated from changes in land cover driven by expansion (or contraction) of crop harvested area and pastureland. We used simulations that linked IMPACT and the Landshift model to derive the relationship between changes in crop area and forest

TABLE 3 Multi-dimensional impacts of increasing commodity and regional agricultural productivity in the target countries.

	Current gross value of production (2017–19 avg)				Simulations of impacts of 25% yield gain (output/ha or output/animal) over 2010 levels in commodity group by 2030^									
	Production value		Poverty-weighted production value		Income		Pop at risk of hunger (caloric adequacy)		GHG emissions		Land use		Irrigation water use	
Commodity scenario	**Value (b$)**	**Parity rule (%)**	**Value (b$)**	**Parity rule (%)**	**Value Δ (b$)**	**Parity rule (%)**	**Value Δ (mil. pop)**	**Parity rule (%)**	**Value Δ (10^6T)**	**Parity rule (%)**	**Value Δ (10^6 ha)**	**Parity rule (%)**	**Value Δ (b m^3)**	**Parity rule (%)**
Cereals	312.4	23.4	48.3	21.5	340.2	21.6	−159.5	49.8	−132.5	33.0	−3.8	29.2	−1.2	41.4
RTB	124.6	9.3	35.7	15.9	124.7	7.9	−37.4	11.7	−17.0	4.2	−1.1	8.5	−0.4	13.0
Oilcrops	34.1	2.6	8.8	3.9	137.8	8.8	−37.8	11.8	−46.4	11.6	−4.3	33.1	1.6	0.0
Pulses	35.4	2.6	8.0	3.6	6.5	0.4	−36.0	11.2	−50.5	12.6	−2.7	20.8	−0.7	23.5
Fruit and Veg	318.5	23.9	49.9	22.2	684.7	43.6	−37.8	11.8	−3.1	0.8	−0.1	0.8	−0.6	22.1
Cash Crops	66.5	5.0	12.7	5.6	80.9	5.1	−11.8	3.7	−15.5	3.9	−1.0	7.7	0.1	0.0
Livestock	443.6	33.2	61.1	27.2	197.4	12.6	4.3	0.0	−135.9	33.9	1.5	0.0	0.1	0.0
SUM	1,335.0	100.0	224.5	100.0	1,572.2	100.0	−316.0	100.0	−400.9	100.0	−11.5	100.0	−1.1	100.0
Regional Scenario					**Simulations of impacts of 25% yield gain over 2010 levels in all commodities by 2030**									
SASIA	433.0	32.4	83.7	37.3	771.1	49.7	−112.7	33.3	−148.3	33.5	−4.0	30.1	−2.7	66.2
SEASIA	244.1	18.3	9.3	4.2	204.2	13.2	−69.3	20.5	−86.3	19.5	−4.5	33.8	1.3	0.0
ESA	111.1	8.3	43.8	19.5	60.3	3.9	−37.7	11.1	−39.9	9.0	−0.7	5.3	−0.8	18.7
WCA	158.2	11.8	60.2	26.8	246.9	15.9	−61.4	18.1	−47.6	10.7	−2.1	15.8	−0.4	9.7
LAC	155.7	11.7	7.2	3.2	12.8	0.8	−21.5	6.4	−50.3	11.3	−0.9	6.8	−0.2	5.5
CWANA	233.1	17.5	20.2	9.0	256.3	16.5	−35.9	10.6	−70.9	16.0	−1.1	8.3	0.5	0.0
SUM	1,335.0	100.0	224.5	100.0	1,551.6	100.0	−338.5	100.0	−443.3	100.0	−13.3	100.0	−2.2	100.0

The analysis focuses on 103 low- and middle-income countries ("target countries") located in six global regions (see Map 1). Excluded are high-income countries, China, Brazil, and Southern Cone countries of South America. Impacts of productivity simulations on agriculture in the target countries produce economic impacts in these countries as well as world-wide through price and trade effects.

The figures in the table only include impacts on the set of target countries except for the GHG metric, which is global. Current gross value of production is 2017–19 average annual quantities produced valued at 2015 prices derived from FAOSTAT.

^Value Δ = change in impact value compared with the projected value in 2030. The simulations assume a 25% increase in yield over this reference yield. The "parity rule" is the relative size of this impact compared with all other groups (it is the % of the sum of impacts across groups).

RTB, roots, tubers, and bananas.

Green-shaded cells show the highest desired outcomes; red-shaded cells indicate undesirable outcomes.

10.3389/fsufs.2022.1031562

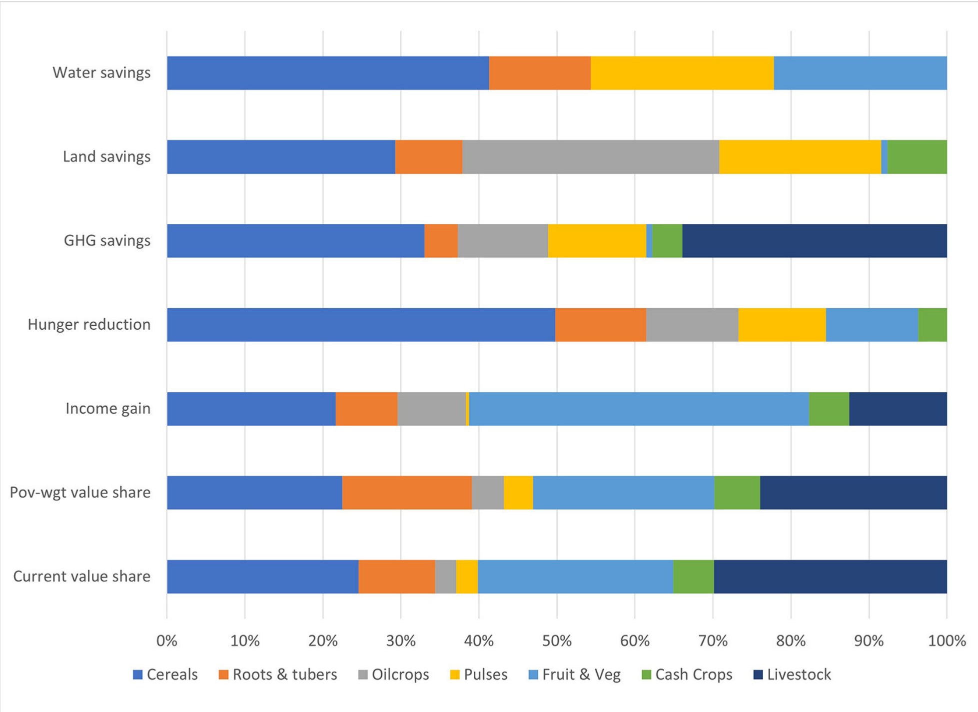


FIGURE 2
R&D allocation parity rule from commodity productivity increases. The parity rule is to allocate R&D in proportion to anticipated benefits or positive impacts. The colors of the bar chart show the relative size of the impacts from productivity growth in the respective commodity groups. The R&D allocation across commodities implied by the parity rule varies depending on policy preferences over type of impact. The figure draws from the estimates reported in Table 2.

area (see especially Schaldach et al., 2011; Rosegrant et al., 2017). 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.

Results

The commodity productivity scenarios assume R&D investment generates a 25% increase in yields (kg of crop/ha, kg of meat/animal or kg of milk/animal/year) by 2030 compared with yields in 2010. In this first set of scenarios, the increase is simulated in one commodity group at a time across the entire set of target countries that are the focus of this analysis. Productivity of other commodity groups and in countries outside the target area is held fixed. The 25% yield increase affects the market price of the affected commodities as well as other commodities through substitution effects. As noted earlier, the simulation model takes into account how producers and consumers respond to the changes in prices and profitability induced by the increase in productivity. Following these adjustments, actual farm yields of affected commodities may change by more or less than 25%. Farm yields of commodities where productivity is held constant may also change since prices of those commodities are also affected. The purpose of this analysis is to determine the relative impacts of increasing productivity on one commodity group vs. another.

Table 3 summarizes results from the simulation model on the multi-dimension impacts of increasing agricultural productivity in seven commodity groups listed in Table 2. The columns show the impacts of commodity productivity on total income, the population at risk of hunger, GHG emissions from agriculture, land use and water use in the target area. For comparison, reference scenario values (projections in 2030 of income, population at risk of hunger, land use, etc., assuming no productivity growth) are provided in Appendix Table A1.

For comparative purposes, Table 3 includes the current value of production and poverty-weighted value of production from the parity model as reported in Fuglie et al. (2022b)[6].

6 Current gross value of production in Table 3 is the annual average quantity harvested in 2017–2019 in billions of metric tons multiplied

TABLE 4 Agricultural productivity and nutritional change in target countries.

	Simulations of impacts on human dietary nutritional adequacy from 25% yield gain in commodity group						
	Zinc adequacy (Zinc)*			Iron adequacy*		Protein adequacy*^	
Commodity scenario	**Change in pop at risk (mil.)**	**RNI ratio**	**Change in RNI ratio (%)**	**RNI ratio**	**Change in RNI ratio (%)**	**RNI ratio**	**Change in RNI ratio (%)**
Reference scenario (no yield change)		1.04		0.83		2.24	
Cereals	−39.89	1.08	3.63	0.87	3.89	2.32	3.24
Roots and tubers	−9.20	1.05	0.69	0.84	0.83	2.25	0.50
Oilcrops	−9.49	1.05	0.77	0.84	0.71	2.25	0.59
Pulses	−10.27	1.05	0.84	0.84	0.83	2.26	0.73
Fruit and vegetables	−6.56	1.05	0.61	0.84	0.81	2.26	0.61
Cash Crops	−3.93	1.05	0.35	0.84	0.46	2.25	0.26
Livestock	−1.29	1.04	0.19	0.83	−0.07	2.25	0.24

*For nutrients other than zinc, the relationship between dietary nutrient availability and population at risk from dietary inadequacy is not well established. For many nutrients, dietary adequacy of a particular nutrient may be dependent on other factors, such as access to sanitation, clean water and availability of complementary nutrients in the diet.
The RNI ratio provides a measure of overall nutrient availability in the diets of a population. It is the ratio between average per capita nutrient availability in diets and the recommended nutrient intake (RNI). An RNI ratio of 1.00 implies that on average per capita nutrient availability just equals the recommended daily intake of that nutrient. For a population with an RNI ratio of 1.00, it is likely that half the population (those consuming below the mean) will have inadequate nutrient availability and half the population (those consuming above the mean) will have adequate availability of the nutrient in their diet. As RNI rises, a larger share of the population will experience adequate nutrient availability in their diet.
^Protein adequacy depends not only on the quantity but also the quality of protein. The simulation model only considers the quantity of protein availability in the diet.
Green-shaded cells show the highest desired outcomes; red-shaded cells indicate undesirable outcomes.

If the economic impacts of commodity research are strongly correlated with the current economic value of the commodities, and if the R&D costs of raising productivity are roughly similar among commodities, then the value shares from the parity model indicate an efficient R&D allocation rule that is likely to maximize economic returns across the commodity R&D portfolio. With a couple of exceptions, the value shares of the commodity groups from the parity model are strongly correlated with the share of projected income gains from the simulation model. However, the simulation model indicates a relatively greater potential value for fruits and vegetables and less for livestock than the parity model. The higher potential value for fruits and vegetables may arise because of the strong growth in demand projected by the simulation model for these commodities. For livestock, the simulation model may better reflect the income gains from value-added activities in this sector. Since a large share of the final value of livestock is from crops used for animal feed, using the gross value of livestock output (which the parity model uses) may overstate the economic importance of this sector.

by the global average farmgate prices in 2014–2016 international dollars per ton (FAOSTAT, 2021). Poverty-weighted values multiply each country's gross value of production by its $1.9/capita/year poverty rate (World Development Indicators, 2021) and aggregates these values by commodity across the target area and by region.

Impacts on income growth, population at risk of hunger, and natural resources

From the simulation model, the largest impacts on economic or income growth arise from an increase in the productivity of fruits and vegetables, followed by cereal grains. Productivity increases in fruits and vegetables are projected to make only small improvements in the other dimensions of impact, however. Productivity improvement in cereal grains is projected to have much larger impacts on decreasing the population at risk of hunger and conserving natural resources—reducing agricultural land, water use, and GHG emissions.

For each of these impact dimensions, the "parity rule" is applied to the simulation results to indicate how R&D might be allocated across commodity programs in order to maximize the impact of R&D on that objective. Figure 2 depicts the "R&D allocation parity rule" graphically for each of the impact dimensions. For example, an R&D allocation to maximize economic or income growth would allocate 22% of funds to cereal grains, 44% to fruits and vegetables, and the rest shared among the other commodities; a focus on hunger reduction would allocate nearly 50% of R&D just to cereals and only 12% to fruits and vegetables, while a sole emphasis on reducing GHG emissions would allocate 34% of R&D funds to livestock, 33% to cereal grains, and less than 1% to fruits and vegetables. A decision-maker wishing to address several of these objectives at once would need to balance the R&D portfolio allocation accordingly.

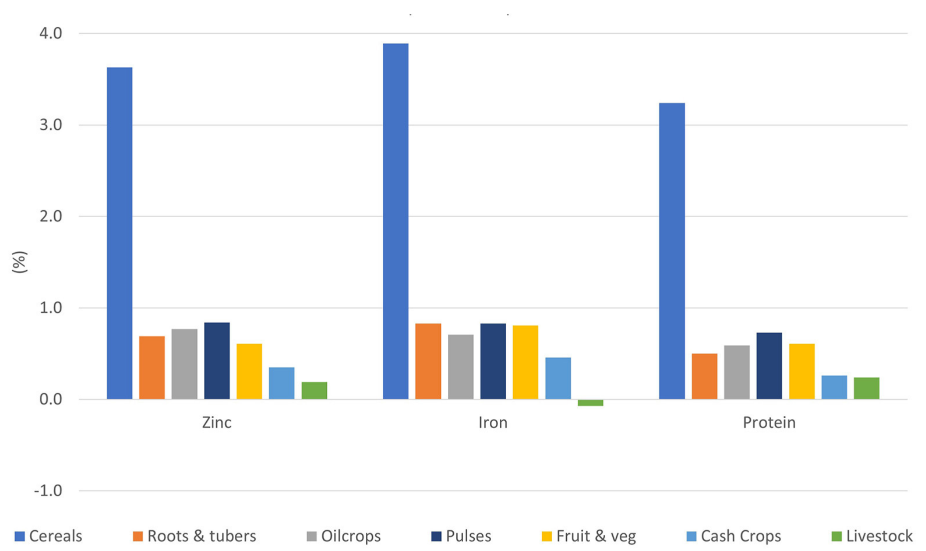


FIGURE 3
Changes in RNI ratios for protein, iron and zinc from increases in commodity productivity. The figure shows the percentage change in RNI ratios for three nutrients resulting from productivity growth in the respective commodity groups. The figure draws from results reported in Table 3.

The bottom half of Table 3 shows the effects of raising productivity of all commodities within a region. In these scenarios, productivity is increased in one region at a time and compared against the baseline scenario of no productivity change. This allows a comparison across regions of where agricultural productivity will have a relatively greater or lesser impact on the outcomes of interest. Although productivity growth is confined to one region, the resulting effects will be worldwide due to markets (e.g., price changes) and trade. The impacts reported in Table 3 include the total impact on the 103 countries in the target area but exclude impacts on the rest of the world. Note that the sum of the simulated impacts of the commodity scenarios is not equal to the sum of the impacts across regions. This is because the commodity and regional scenarios have different implications for prices, utilization and trade.

Agricultural productivity growth in South Asia has by far the largest impact on income growth and hunger reduction among the six regions, due to its relatively large agricultural sector and the size of its low-income, rural population. The South Asia scenario also resulted in a greater reduction in agricultural GHG emissions compared. Next in importance for food security impacts were West & Central Africa and Southeast Asia.

Some other results from Table 3 are worth highlighting:

- Productivity gains in livestock are projected by the simulation model to substantially reduce GHG emissions but could increase the population at risk of hunger. Ruminant livestock especially are a major source of GHG emissions from enteric fermentation, manure, and fertilizers used on feed crops. Productivity improvement in livestock lowers the prices of animal products while raising the prices for feed and food crops. Overall, the productivity gains reduce the number of animals needed to meet market demand, resulting in significantly fewer GHG emissions. The higher prices for crops, however, make these staples less affordable.
- Productivity growth in smallholder cash crops like coffee, cocoa and cotton is more important for income generation than hunger reduction. Since these crops are principally for export, they have little or no effect on domestic prices of food staples. Thus, beneficiaries of the income gains are primarily local producers rather than local consumers.
- The most significant reductions in agricultural land use come from productivity gains in crops that are grown over wide areas: namely, oilcrops, cereal grains, and pulses. Productivity gains in livestock, however, are projected to increase cropland in order to produce more feed.
- The most significant savings in water use come from productivity gains in crops that dominate irrigated areas: cereal grains, fruits and vegetables, and pulses. Productivity gains in oilcrops are projected to increase water use: higher productivity leads to less area in oilcrops which are then replaced by more water-intensive crops in irrigated areas.

The relative size of the impacts of agricultural productivity on income, hunger reduction and natural resource use is likely to vary by region and country (see the Appendix Tables A2–A7 for the regional breakdown of the impacts from the commodity

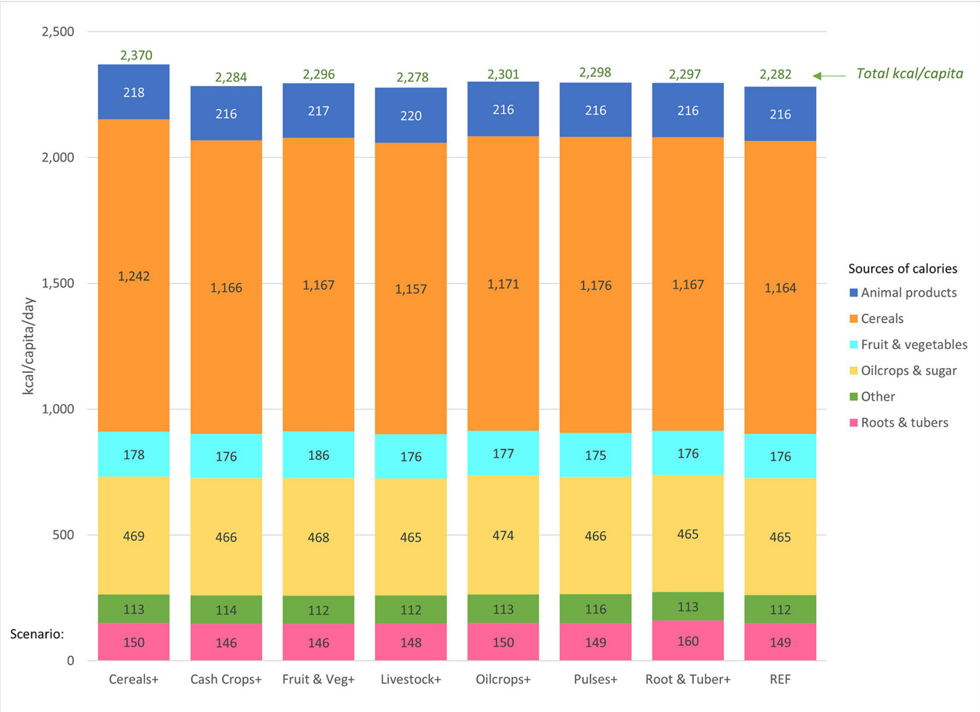


FIGURE 4
Sources of calories in the average consumer diet under commodity productivity scenarios. Scenario: commodity demand is based on population and income projections for 2030. The reference scenario (REF) holds commodity yields at 2010 levels. The other scenarios increase the yield of each commodity group by 25% over the 2010 yield level while holding yields of other commodities unchanged. Consumers adjust food consumption in response to relative price changes among commodities.

productivity scenarios). These table allocate the impacts of the commodity scenarios among the six regions. Some highlights from the regional results include:

- Although improving agricultural productivity saves natural resources overall in the 103 countries, in some regions and for some crops, productivity gains increase emissions, land use, or water use;
- Productivity gains in fruits and vegetables are projected to be particularly important sources of income growth in South Asia, SE Asia, and CWANA;
- For West & Central Africa, improving the productivity of root and tuber crops ranks first for income growth and second for hunger reduction, behind cereal grains.
- For the Latin American countries included in the target area, raising the productivity of cash crops (primarily smallholder coffee) is more important than cereals as a source of income growth and for saving land.

Impacts on nutrient availability

Besides caloric intake (used to measure the population at risk of hunger), the simulation model assessed the impact of agricultural productivity on dietary intake of zinc, iron and protein across the commodity productivity scenarios. Zinc and iron are micronutrients, while protein along with carbohydrates and fat is classified by nutritionists as a macronutrient. Significant numbers of people in the target countries suffer adverse health consequences from inadequate dietary intake of all three nutrients (Global Nutrition Report, 2021). For protein, not only quantity but also quality (i.e., content of essential amino acids) is important for dietary health. However, this analysis only considers the quantity of protein in the diet.

The primary measure we use to assess the impact of productivity on nutrition is the change in its RNI ratio: the ratio between per capita daily availability of a nutrient in average diets and its Recommended Nutrient Intake (RNI). An RNI ratio of 1.00 implies that the per capita nutrient availability in the average diet just equals its RNI. For a population with an RNI ratio of 1.00, it is likely that half the population (those consuming less than average quantities of food per capita) will have inadequate nutrient availability and half the population (those consuming above average quantities of food) will have at least adequate availability of the nutrient in their diet. As RNI rises, a smaller share of the population will experience inadequate nutrient availability in their diet. For some nutrients, consuming significantly above the RNI may have harmful effects on health. For other nutrients, excess nutrients are either stored in the body or passed out as body waste.

For all three of these nutrients, increasing the productivity of cereal grains has by far the largest impact on raising dietary adequacy in the target area (Table 4). A 25% increase in cereals productivity increased the RNI ratio by more than 3% in the target countries, compared with less than 1% for productivity gains in the other commodities (Figure 3). For zinc, changes in dietary intake were also translated into changes in the population at risk from dietary inadequacy of this nutrient. Increasing the productivity of cereal grains was projected to reduce the population at risk from inadequate zinc by 40 million persons, about four times higher than the next best alternative, pulses, which would reduce the population at risk by just over 10 million people.

One reason for the relatively large impact of cereals on nutrition is because these crops are a major source of not only carbohydrates but also protein and many micronutrients in diets. Another reason is that cereal grains typically account for share of expenditures by low-income households. Raising the productivity of staple foods lowers their price, making these foods more affordable and thus increasing real household purchasing power. This enables households to diversify their diets away from food staples to more income-elastic products like meat, dairy, fruits, and processed foods. For food staples with a high household expenditure share, a given percent decline in its price will have a larger effect on household purchasing power compared with other foods purchased by the household and allow for more dietary diversification.

How commodity productivity affects dietary composition is illustrated in Figure 4. The reference case (REF) shows the contribution of each food group to total calories consumed in an average diet in the target area assuming no productivity gains by 2030. The other bars show how diets change when the productivity of each commodity group is increased by 25% above the reference case. This estimate is derived by using empirical evidence on how consumers are likely to respond to changes in the relative prices of foods.

In all scenarios, cereal grains contribute about 51% of total calories, which rises to 52.4% (or 1,242 kcal/capita/day from cereals) when cereals productivity alone is increased. Note that raising productivity in one food group increases the consumption of all food groups. Raising cereals productivity, for example, increases the caloric contribution of fruits and vegetables from 176 kcal/capita/day to 178 kcal/capita/day.

Raising fruit and vegetable productivity has an even larger effect on that food group, raising its contribution to 186 kcal/capita/day. This is because the fruit and vegetable productivity gain lowers the relative price of these foods compared with other food groups. But because the expenditure share of fruits and vegetables is less than that of cereals, it has a smaller effect on the consumption of other food groups. Overall, productivity growth in fruits and vegetables results in a smaller increase in the RNI ratios of carbohydrates, protein, zinc and iron compared with the cereals scenario. Similarly, the livestock productivity scenario raises the number of calories from livestock products more than the other scenarios, but with a reduction in total calories compared with the reference scenario.

Simulated impacts of agricultural productivity on average dietary composition were also estimated for each region. In all regions, raising the productivity of cereal grains had the largest impact on total calories, protein, zinc, and iron consumed. Because results were similar across regions, results for individual regions are not included in the paper.

Essentially, the largest impacts on reducing macro and micronutrient inadequacy in diets occur when the average price of food declines the most. Since cereal grains make up the largest component of overall food price (and household expenditure share), raising productivity in cereals generates the largest gains in nutritional adequacy.

For middle- and upper-income countries, overconsumption of calorie-rich foods is contributing to rising rates of obesity and related health problems. These foods are often highly processed and designed for their convenience and taste. Food and nutrition policies and regulations can encourage the consumption of nutrient dense foods (defined as foods that have high nutrient content per calorie). For low and lower-middle income countries, underconsumption of macro and micronutrients affects a large share of the population and is the major driver of food insecurity and malnutrition. Agricultural R&D funding to lower the cost of the foods with the largest household budget share can significantly improve dietary adequacy and quality.

Discussion

Quantitative economic analysis provides a powerful set of tools for informing decisions about agricultural R&D priorities and funding allocation. While investment in international agricultural R&D has been shown to generate high returns on average, impacts are multidimensional and vary depending on the focus of the research undertaken. The analysis in this paper shows there are significant differences in potential impacts of productivity growth (and R&D investment) across agricultural commodities and regions in the Global South. Some commodities offer greater potential to increase economic or income growth, while productivity improvement in other commodities might have relatively greater effects on food security, nutrition or natural resource conservation. Which commodities offer the greater potential to advance objectives also depends on the region for which the research is undertaken.

Simulations of projected impacts from increasing productivity in different commodity groups in the target area (103 low- and middle-income countries spanning six regions covering Africa and parts of Asia and Latin America) reveal potential tradeoffs among research objectives of maximizing income growth, reducing hunger, improving nutrition, and conserving natural resources:

- Productivity increases in Fruits and Vegetables offer the highest contribution to income growth, closely followed by Cereal Grains.
- Productivity increases in Cereal Grains generate the largest reduction in the population at risk of hunger.
- Productivity increases in Cereal Grains result in the largest increase in per capita nutrient availability for protein, zinc, and iron (the only nutrients other than calories analyzed in the simulations).
- Productivity increases in Cereal Grains and Livestock offer the largest potential for reducing agricultural greenhouse gas emissions.
- Productivity increases in crop commodities are land sparing, with the largest land savings obtained by raising productivity of area-extensive crops (i.e., Cereal Grains, Oilcrops and Pulses).
- Comparing the R&D allocations suggested by the parity rule, productivity increases in Fruits and Vegetables, Livestock and smallholder Cash Crops have relatively greater potential to generate income growth than to reduce hunger: their parity percentages are higher under the "income" outcome than under the "population at risk of hunger" outcome.
- In the Latin American countries included in the analysis, Cash Crops (especially coffee) offer greater potential to generate income growth than cereal staples.
- In West & Central Africa, productivity increases in Roots and Tubers offer the highest potential among commodity groups to generate income gains while increasing productivity in Cereal Grains offers the greatest potential to reduce hunger.

Besides informing R&D allocation across programs and projects, the results in this report also shed light on important strategic questions currently facing international agricultural research. For example, one question is whether shifting R&D investment away from crop staples to fruits and vegetables would increase the dietary availability of key micronutrients. The quantitative models used in this study suggest that while demand for fruits and vegetables is growing rapidly and higher productivity of these crops offers significant potential to raise incomes of smallholder producers, investing in the productivity of cereal staples offers significantly greater opportunities to increase nutrient availability of protein, iron, and zinc (and possibly other micronutrients as well) in the diets of low-income consumers, as well as reduce the population at risk from hunger due to inadequate caloric intake.

A second concern facing funders of international agricultural R&D is whether investing in ruminant livestock productivity would exacerbate greenhouse gas (GHG) emissions from agriculture. While raising livestock productivity would likely reduce emissions per unit of meat and milk produced, it would also lower prices and thus stimulate more total demand for these products. Our quantitative analysis indicates that the net effects of raising productivity in ruminant livestock could significantly lower GHG emissions from agriculture. In fact, increasing the productivity of cereal grains and ruminant livestock would likely have the largest impact on reducing GHG emissions from agriculture in the target countries compared with productivity improvement in other commodities.

A third strategic question for international agricultural research is whether investing in small holder cash crops might offer significantly greater opportunities than food crops in raising incomes and reducing poverty and hunger. Our findings suggest that for comparable rates of productivity growth, smallholder cash crops like cocoa, cotton, and coffee generally offer less potential impact on income, nutrition, and natural resource conservation than productivity growth in staple food crops. However, in Central America and the Andes region of Latin America, raising the productivity of cash crops (especially coffee) may have as much or greater potential impact on income as raising the productivity of maize, a major food staple of the region.

The "answers" to these strategic questions are of course conditional on (and limited by) the quality of data and modeling assumptions used in the analysis. Results can be always challenged—and improved upon—with the development of better data and models. A key strength of these models, however, is that they consider how increases in agricultural productivity are likely to affect commodity prices, and how these price changes, in turn, may affect what producers choose to produce and what consumers choose to consume, while assuring that market supply equals market demand. Decision makers also need to consider that R&D investment is not the only policy instrument to address these multiple objectives. If other policies can more effectively address specific environmental concerns (e.g., land and water policies) or nutritional needs of vulnerable populations (such as food assistance policies), then reallocating R&D spending toward these ends may not be the most efficient policy choice, especially if it entails a significant reduction in economic growth (Alston et al., 2016).

One limitation of this analysis is that we only consider commodity-oriented research that raises productivity. We do not consider potential impacts of other kinds of food and agricultural research, including research on policies, food and nutrient, forestry and fisheries. Reardon et al. (2018) argue that rapid transformation of agri-food systems needs to take into account research and innovations in the entire agri-food value chain. However, there are good reasons for our focus on R&D to raise commodity productivity. For one, this is an area where public support is especially needed to develop locally adapted technologies. Innovations in food processing generally have stronger private sector incentives to develop and are easier to transfer across food systems and countries. Second, commodity-oriented international research has repeatedly demonstrated high returns, while evidence on returns to non-commodity agricultural research is considerably thinner (Renkow and Byerlee, 2010).

Another limitation of the approach used in this study to R&D prioritization is its singular focus on demand-side considerations. We have ignored potentially significant differences across commodities and regions in the R&D and extension costs to develop and disseminate new technologies to farmers. Fuglie et al. (2019) outline a number of features of an "enabling environment" that may constrain adoption of farm technologies, including adverse price policies, poor rural infrastructure, insecure land tenure, limited access to financial and insurance services, and low levels of education and extension services. However, these constraints are likely to be highly contextual and location-specific; taking into account these factors in R&D prioritization may be better addressed in the project selection stage of commodity research rather than at the programmatic stage of international R&D resource allocation (see Footnote 2).

A final point on optimizing resource allocation in international agricultural research is that it depends on having a transparent and consistent accounting system to track R&D investments. The CGIAR system, lacks a system for categorizing its research expenditures and it is hard to determine how much is being allocated to any commodity or other problem area (Thorton et al., 2022). Ideally, a research allocation accounting system should classify research expenditure and science-years across several criteria, including by commodity or resource, by problem area or activity, and by field of science, as well as by institution and location where the research is conducted. This would be an invaluable tool for evidence-based decision-making in the planning and management of international agricultural research.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KF and KW contributed to conception and design of the study. KF, TS, NC, and DW performed statistical analysis. KF wrote the first draft of manuscript. KW, TS, and NC contributed to manuscript revision, read, and approved the submitted version. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the U.S. Agency for International Development and the U.S. Department of Agriculture.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Author disclaimer

The findings and conclusions in this report are those of the authors and should not be construed to represent any official USAID, USDA or U.S. Government determination or policy.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1031562/full#supplementary-material

References

Alston, J. M., Chan-Kang, C., Marra, M. C., Pardey, P. G., and Wyatt, T. J. (2000). *A Meta-Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem?* Research Report 113. Washington, DC: International Food Policy Research Institute (IFPRI).

Alston, J. M., MacEwan, J. P., and Okrent, A. M. (2016). Effects of U.S. public agricultural R&D on U.S. obesity and its social costs. *Appl. Econ. Perspect. Policy* 38, 492–520. doi: 10.1093/aepp/ppw014

Alston, J. M., Norton, G. W., and Pardey, P. G. (1995). *Science Under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*. Ithaca, NY: Cornell University Press.

Alston, J. M., Pardey, P. G., and Rao, X. (2020). *The Payoff to Investing in CGIAR Research*. Washington, DC: SoAR Foundation.

ASTI (2022). *Agricultural Science and Technology Indicators online database*. Washington, DC: International Food Policy Research Institute (IFPRI) (accessed September 21, 2022).

Beach, R. H., Sulser, T. B., Crimmins, A., Cenacchi, N., Cole, J., Fukagawa, N. K., et al. (2019). Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. *The Lancet Planetary Health* 3, e307–e317. doi: 10.1016/S2542-5196(19)30094-4

FAO (2008). *FAO Methodology for the Measurement of Food Deprivation Updating the Minimum Dietary Energy Requirements. Rome: Food and Agriculture Organization of the United Nations*. Available online at: http://www.fao.org/fileadmin/templates/ess/documents/food_security_statistics/metadata/undernourishment_methodology.pdf (Accessed October, 2018).

FAOSTAT (2021). *Agricultural Statistical Time Series*. Rome, Italy: Food and Agriculture Organization of the United Nations. Available online at: http://faostat.fao.org/ (accessed January 15, 2021).

Fuglie, K. (2016). The growing role of the private sector in agricultural research and development world-wide. *Glob. Food Secur.* 10, 29–38. doi: 10.1016/j.gfs.2016.07.005

Fuglie, K., Gautam, M., Goyal, A., and Maloney, W. (2019). *Harvesting Prosperity: Technology and Productivity Growth in Agriculture*. Washington, DC: World Bank. doi: 10.1596/978-1-4648-1393-1

Fuglie, K., Ray, S., Baldos, U. L. C., and Hertel, T.W. (2022a). The R&D cost of climate mitigation in agriculture. *Appl. Econ. Perspect. Policy*. doi: 10.1002/aepp.13245

Fuglie, K., Wiebe, K., Prager, S., Sulser, T. B., Cenacchi, N., Bonilla-Cedrez, C., et al. (2022b). *Quantitative Analysis to Inform Priorities for International Agricultural Research*. IFPRI Discussion Paper 02133. Washington, DC: International Food Policy Research Institute. doi: 10.2499/p15738coll2.136357

Global Nutrition Report (2021). *The Status of Global Nutrition*. Bristol, UK: Development Initiatives.

Gomez, M. I., Barrett, C. B., Raney, T., Pinstrup-Andersen, P., Meerman, J., Croppenstedt, A., et al. (2013). Post-green revolution food systems and the triple burden of malnutrition. *Food Policy* 42, 129–138. doi: 10.1016/j.foodpol.2013.06.009

Hurley, T. M., Rao, X., and Pardey P. G. (2018). Reexamining the reported rates of return to food and agricultural research and development. *Amer. J. Agric. Econ*. 96, 1492–1504. doi: 10.1093/ajae/aau047

IPCC (2006). "Emissions from livestock and manure management," in *2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry, And Other Land Use*, eds S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (Cambridge, United Kingdom: Cambridge University Press), Chapter 10.

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., et al. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* 122, 387–400. doi: 10.1007/s10584-013-0905-2

Pardey, P. G., Chan-Kang, C., Dehmer, S. P., and Beddow, J. M. (2016). Agricultural R&D is on the move. *Nature* 15, 301–303. doi: 10.1038/537301a

Pemsl, D., Staver, C., Hareau, G., Alene, A. D., Abdoulaye, T., Kleinwechter, U., et al. (2022). Prioritizing international agricultural research investments: lessons from a global multi-crop assessment. *Res. Policy* 41, 104473. doi: 10.1016/j.respol.2022.104473

Reardon, T., Echeverria, R., Berdegue, J., Minten, B., Liverpool-Tasie, S., Tschirley, D., et al. (2018). *Rapid Transformation of Food Systems in Developing Regions: Highlighting the Role of Agricultural Research and Innovations*. AgEcon Search Open Access Agricultural and Applied Economics Digital Library, University of Minnesota, St. Paul, MN. Available online at: https://E:/3%20Project_CGIAR-USAID%20ag%20RD%20priorities%202021/4_Literature/Reardon_food%20systems%20innovation_2018.pdf (Accessed October, 2022).

Renkow, M., and Byerlee, D. (2010). The impacts of CGIAR research: a review of recent evidence. *Food Policy* 35, 391–402. doi: 10.1016/j.foodpol.2010.04.006

Robinson, S., Mason d'Croz, D., Islam, S., Sulser, T. B., Robertson, R. D., Zhu, T., et al. (2015). *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3*. Washington, DC: International Food Policy Research Institute (IFPRI). doi: 10.2139/ssrn.2741234

Rosegrant, M. W., Sulser, T. B., Mason-D'Croz, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., et al. (2017). *Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio*. Project Report for USAID. Washington, DC: International Food Policy Research Institute. Available online at: https://ebrary.ifpri.org/digital/collection/p15738coll2/id/131144 (Accessed April, 2017).

Rosegrant, M. W., Sulser, T. B., and Wiebe, K. (2022). Global investment gap in agricultural research and innovation to meet Sustainable Development Goals for hunger and Paris Agreement climate change mitigation. *Front. Sustain. Food Sys*. 6, 965767. doi: 10.3389/fsufs.2022.965767

Ruttan, V. W. (1982). *Agricultural Research Policy*. Minneapolis, MN: University of Minnesota Press.

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D. M., Schüngel, J., et al. (2011). An integrated approach to modelling land-use change on continental and global scales. *Environ. Model. Software* 26, 1041–1051. doi: 10.1016/j.envsoft.2011.02.013

Smith, M. R., Micha, R., Golden, C. D., Mozaffarian, D., and Myers, S. S. (2016). Global expanded nutrient supply (GENuS) model: a new method for estimating the global dietary supply of nutrients. *PLoS ONE* 11, e0146976. doi: 10.1371/journal.pone.0146976

Thorton, P., Dijkman, J., Herrero, M., Szilagyi, L., and Cramer, L. (2022). Viewpoint: aligning vision and reality in publicly funded agricultural research for development: a case study of CGIAR. *Food Policy* 107, 102196. doi: 10.1016/j.foodpol.2021.102196

Wessels, K. R., and Brown, K. H. (2012). Estimating the global prevalence of zinc deficiency: results based on zinc availability in national food supplies and the prevalence of stunting. *PLoS ONE* 7, e50568. doi: 10.1371/journal.pone.0050568

Wiebe, K., Sulser, T. B., Dunston, S., Rosegrant, M. W., Fuglie, K., Willenbockel,. D., et al. (2021). Modeling impacts of faster productivity growth to inform the CGIAR initiative on Crops to End Hunger. *PLoS ONE* 16, e0249994. doi: 10.1371/journal.pone.0249994

Willenbockel, D., Robinson, S., Mason d'Croz, D., Rosegrant, M. W., Sulser, T. B., Dunston, S., et al. (2018). *Dynamic Computable General Equilibrium Simulations in Support of Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio: Linking the IMPACT and GLOBE Models*. IFPRI Discussion Paper 1738. Washington, DC: International Food Policy Research Institute (IFPRI). Available online at: http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/132757 (Accessed July, 2018).

World Development Indicators (2021). Washington, DC: World Bank (accessed December 10, 2021).

World Resources Institute (2019). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. Washington, DC: World Resources Institute.

Yan, X., Akiyama, H., Yagi, K., and Akimoto, H. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Glob. Biogeochem. Cyc.* 23, GB2002. doi: 10.1029/2008GB003299

frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 10 November 2022
DOI 10.3389/fsufs.2022.965011

Check for updates

OPEN ACCESS

EDITED BY
Julia Compton,
Independent Researcher, Cardiff,
United Kingdom

REVIEWED BY
Johannes S. C. Wiskerke,
Wageningen University and
Research, Netherlands
Andrew Hamilton,
University of Melbourne, Australia

*CORRESPONDENCE
Gordon Prain
gprain50@gmail.com

SPECIALTY SECTION
This article was submitted to
Land, Livelihoods and Food Security,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 09 June 2022
ACCEPTED 12 October 2022
PUBLISHED 10 November 2022

CITATION
Prain G, Simon D, Halliday J and
Drechsel P (2022) Investment priorities
for research and innovation in urban
agri-food systems: Toward more
resilient cities in the Global South.
Front. Sustain. Food Syst. 6:965011.
doi: 10.3389/fsufs.2022.965011

Investment priorities for research and innovation in urban agri-food systems: Toward more resilient cities in the Global South

Gordon Prain[1]*, David Simon[2,3], Jess Halliday[4] and Pay Drechsel[5]

[1]Resilient Cities Initiative, CGIAR, Cambridge, United Kingdom, [2]Commission on Sustainable Agricultural Intensification, London, United Kingdom, [3]Department of Geography, Royal Holloway, University of London, London, United Kingdom, [4]RUAF Global Partnership on Sustainable Urban Agriculture and Food Systems, Den Haag, Netherlands, [5]Resilient Cities Initiative, International Water Management Institute, Colombo, Sri Lanka

Urban and peri-urban agriculture (UPA) is widely distributed throughout the Global South. Despite urban population growth and diversifying food habits, UPA delivers an important part of urban food supply, as well as other types of services to cities, such as employment and waste reuse. Nevertheless, the extent and importance of UPA varies between different urban areas, while challenges like limited recognition, land conversion, and water pollution and competition threaten the potential of UPA to contribute to urban resilience. Key investment priorities for research and innovation for overcoming current challenges include incentivized peri-urban zoning, urban allocation of productive lands, and increasing capacities for controlled environment agriculture (CEA). Innovative repositioning of food marketing can help to strengthen supply of healthy food from UPA production, increase decent employment, and turn food markets into nutrition hubs. Priority innovations for contributing to the circular bioeconomy of cities include scaling the safe use of wastewater for irrigation through investments in the adoption of multiple risk-barrier approaches and scaling UPA-based ecosystem services for valorising solid waste and environmental management. Innovations in urban governance are required to support these processes by bringing food systems into urban planning through food mapping and the multisectoral platforms for dialogue and policy formulation across city regions and with vertical levels of government.

KEYWORDS

urban agriculture, food systems, controlled environment agriculture, informal markets, circular bioeconomy, resource recovery, city-region, food governance

Introduction

Ensuring sustainable and secure supplies of appropriate quality food for urban populations that do not exacerbate the climate crisis is a major global challenge. Eighty percent of global food production now ends up in cities, but only around 63% is consumed. The rest, about 931 million tons, becomes food waste (UNEP, 2021). The challenge of feeding cities is most acute in the Global South where most food loss occurs during harvest, storage, and transportation, while poor (food) waste management poses a public and environmental health problem for cities. A double burden of malnutrition afflicts low-income countries, with perhaps 300 million urban residents going hungry, while an epidemic of obesity and non-communicable diseases (NCDs) increasingly affects the poor in the Global South, primarily driven by increasing consumption of sugars, fat, and salt in processed foods (Popkin et al., 2012; Vilar-Compte et al., 2021). These nutritional challenges are being accelerated by urbanization processes and climate change. By 2050, two-thirds of the Global South population will be urban, while urban expansion is currently occurring mostly through slum and informal settlement growth (UN-Habitat, 2020). Informal employment, especially of women and men in food and other retail services, accounts for up to 80% of the total in some cities in the Global South (ILO, 2018). Inadequate and precarious incomes and congested housing conditions affect both economic and physical access to healthy food.

Large, "core" cities as well as small and medium "secondary" cities (Cardoso, 2022) have largely underappreciated opportunities to alleviate some of these stresses on urban food access and climate change by developing the actual and potential food supply within urban areas and from the surrounding urban foodsheds (Schreiber et al., 2021), which include peri-urban and nearby rural areas, i.e., from within city regions (Dubbeling et al., 2016, 2017; Blay-Palmer et al., 2018; Acharya et al., 2020). Up to 70% of the world's population is already living in these areas (Berdegué et al., 2014), food for about 30% of this population is produced there (Kriewald et al., 2019), and it is where most food marketing occurs. Accordingly, these are the spaces with the greatest opportunities to build the urban circular bioeconomy through recovering the vast volumes of solid and liquid urban waste and reusing them in nearby agricultural processes, as well as contributing to associated ecosystem services like flood reduction (Dubbeling et al., 2016; Evans et al., 2022). Moreover, where political instability, epidemics, or economic crisis accelerate challenges related to urban food supply, farming within or close to cities—urban and peri-urban agriculture or UPA—can help build urban resilience and is an increasing focus of attention (Malec et al., 2022; Yan et al., 2022).

For cities to take up these opportunities, investment is needed in innovations that will enable these different components to contribute more effectively to resilient cities and city regions (Prain, 2022). This paper suggests priorities for investment in research and innovation in UPA, based on two recent non-systematic reviews of recent literature (Halliday et al., 2021; Prain, 2022) and the extensive personal experience of the authors. Sections Protecting productive land, boosting productivity, Repositioning informal food markets, and Recovering water and waste for the urban circular bioeconomy highlight innovations needed in agricultural production, food marketing, and in the productive reuse of otherwise wasted natural resources, like organic waste, characteristics of the circular bioeconomy (Carus and Dammer, 2018). However, this also requires innovations in the governance and planning environment. Production, marketing, and resource recovery and reuse often occur across spatial and sectoral boundaries and involve different levels of government. Section Innovating food systems planning and governance to support UPA considers some of the institutional innovations needed to facilitate effective and sustainable agri-food systems.

Protecting productive land, boosting productivity

Most agriculture within urban areas is practiced on small areas of land, often for subsistence, with surpluses exchanged or sold within the community (Prain, 2022). Where urban and especially peri-urban agriculture is practiced at a larger scale, outputs can be locally important as an urban food source. Furthermore, producing close to the place of consumption can shorten food supply chains and enhance trust between producers and consumers, as well as reduce transportation costs, emissions, and the risk of food loss due to poor infrastructure (Vittersø et al., 2019).

However, lack of secure land tenure is a significant barrier, especially in the context of rapid urbanization and land-use tensions arising between agriculture, business, and formal and informal residential settlements (Mougeot, 2000). People who grow crops on public land often face harassment and eviction by law enforcement agencies (Foeken, 2004; Prain, 2010; Cabannes and Marocchino, 2018).

Some local governments (for example Quito in Ecuador and Rosario in Argentina) have established programmes for urban residents to grow food on government-owned land to boost household food security and generate income through the sale of surplus (Prain, 2022). Examples of other innovative mechanisms with potential to secure land access in the face of urbanization pressures and political change include the following:

- Designation of urban agriculture zones in urban development plans, as provided for in the Nairobi Urban Agriculture Promotion and Regulation Act 2015 in Kenya (IPES-Food, 2017).

- Creation of a municipal land bank, a mechanism for registering and allocating the right to use public spaces that are suitable for growing food, as done in Rosario (Halliday et al., 2019).
- Shared governance, such as community land trusts in the United Kingdom that ensure joint stewardship of land and resources by local organizations and municipal governments (Community Land Trust Network, 2022).
- Failure to embed such programs within policy frameworks, can make them vulnerable to electoral change.

Increasing UPA productivity sustainably is an important area of innovation (Taylor, 2020). Some forms of controlled environment agriculture (CEA) can deliver high yields on very small areas of land (Artemis, 2020). Hydroponic and aquaponic systems that maximize natural energy sources (such as natural sunlight or gravity-fed watering) and local materials (such as coco coir, coco peat, perlite, or other by-products of local industry), practiced in greenhouses and polytunnels, are suitable for food growing in cities in the Global South, where land is expensive and may be contaminated, and at larger scales in peri-urban areas (von Kaufmann, 2018; Halliday et al., 2021).

Although there is potential for some forms of CEA to complement rural systems' ability to provide urban communities with fresh produce, CEA is not a silver bullet for urban food security or sustainable development in the Global South. Start-up and running costs are high, as is the risk of failure, especially where no local training or tailored extension services are available (Halliday et al., 2021). As such, CEA entrepreneurship depends heavily on access to funds and education and training. Practitioners of CEA often seek to recoup start-up costs by charging a premium or focusing on specialty crops for high-income consumers that command a higher price than varieties that are traditionally grown in the area and form part of local diets. Some pledge to reduce their prices or to switch to local varieties once they are technically and economically feasible, but there is no firm indication of when that may happen. Until—or unless—it does, the contribution of CEA to food and nutrition security will be minimal (Pinstrup-Andersen, 2018; Halliday et al., 2021). For the potential of CEA to be realized in the Global South, there is a need for significant investment in several areas:

- Removal of entry barriers associated with investment costs through innovative approaches to accessing start-up funding through public and private sector actions (Cabannes, 2015);
- Improved operational viability through tailored training and extension services;
- Research into CEA cultivation of local crops that are traditionally grown and consumed locally, especially throughout the year to reduce price fluctuations (Jensen, 2002; Mytton-Mills, 2018);
- Research into CEA techniques to minimize energy use, reduce environmentally harmful practices, and optimize efficiency within specific local contexts (Halliday et al., 2021);
- Adaptation of technologies used in high income countries to suit the specific needs and challenges in lower income contexts, incentivized through trade and development programmes (Halliday et al., 2021).

Repositioning informal food markets

With 55% of global food consumers now living in urban areas and almost 80% of global food production destined for urban consumption (FAO, 2019), there is increasing pressure on urban market systems to provide stable physical and economic access to food. Although informal food vendors make a major contribution to urban food systems (Giroux et al., 2021), the evidence from many cities in the Global South suggests that urban physical markets are struggling to respond to needs (Davies et al., 2021). A study covering 171 urban food systems in Asia suggests that informal food markets and street food are simultaneously "the most valuable and problematic parts" of those systems (Acharya et al., 2020, p. 94). Physical access is frequently difficult for sellers, market support workers, and buyers. Especially in the case of retail markets, infrastructure is often limited, including lack of adequate lighting, toilet facilities, and clean water (Marocchino, 2009). These affect food safety (Grace, 2015) as well as gender equity, with women's participation as both vendors and customers made more difficult (Siebert and Mbise, 2018).

Yet these informal markets are where most low-income urban consumers get their fresh food (Crush et al., 2011; Davies et al., 2021) and they are also major sources of employment for the urban poor (Prain, 2022). They have the chance to contribute to urban food system transformation through providing better and more equitable access to safe food and decent employment, as well as reducing carbon emissions though short food supply chains (Crippa et al., 2021). As the main sources of fresh food for the poor, these markets can help reduce obesity and associated NCDs brought on through consumption of processed food high in sugar, fat, and salt, often obtained through fast food outlets and supermarkets (Popkin et al., 2012; Hawkes et al., 2017; Global Nutrition Report, 2020).

To achieve this, there is need to invest in innovative food market repositioning, in terms of functions, infrastructure, spatial locations, and role in public health. *Functional diversification* of food markets highlights opportunities to innovate in the multiple ways that food moves from producers to consumers and emphasizes how diversity in trade as well as in production and consumption can contribute to food system resilience (Hertel et al., 2021). Diversification through repositioning institutional food markets is one opportunity.

These markets account for a significant proportion of total food consumed in cities in the Global South, through schools, hospitals, and via social support programmes (Swensson et al., 2021). Current food procurement policies can be non-transparent and result in long supply chains (Freudenberg, 2016). Understanding and testing innovative policies for targeting procurement from urban and peri-urban suppliers could potentially reduce emissions, improve food safety and quality, and provide increased stimulus to UPA (Kelly and Swensson, 2017).

Another kind of diversification is to strengthen short supply chains between UPA producers and consumers through alternative food sourcing by urban wholesale and retail markets, by drawing on the model of farmers' markets (Hanson et al., 2022). Increased sourcing of food from local producers is now a goal of the World Union of Wholesale Markets (WUWM, 2021) and innovations in retail markets can provide greater access to local food. This can help increase food safety and quality through promoting, for example, ecologically grown, and potentially more trusted products (Arce et al., 2007; Boossabong, 2018; Santandreu, 2018). Low or no packaging combines with reduced transport to contribute to lower emissions.

Market upgrading and decentralization include the urgent need for investment in research-led innovations to improve hygiene and hence food safety through human-centered design approaches (HCD) to sanitary facilities, water provision, and sales points (Lestikow et al., 2017; Sharpe et al., 2019). Such upgrading also needs to involve innovative and mutually acceptable ways to deal with market waste, reduce health risks, and recover an urban resource e.g., for compost (see section Recovering water and waste for the urban circular bioeconomy). A crucial emerging research and investment priority relates to improving phytosanitary conditions in wet markets to avoid cross-species viral infections, such as may have triggered the COVID-19 pandemic from Wuhan's wet market (Open Access Government, 2022).

Sometimes, upgrading may include innovative processes of decentralization, especially where access becomes a major constraint. A primary consideration for market upgrading and decentralization is the need for participatory consultation with stakeholders, to avoid actions that do not appropriately take account of user needs, cultural practices, and capacities (Marocchino, 2009; Song and Taylor, 2018; Acharya et al., 2020).

To confront the urban crisis of unhealthy eating and obesity, multiple approaches have been attempted, including efforts to change the market environment through laws and incentives, and efforts to increase informed choice (Brambila-Macias et al., 2011; Hawkes et al., 2017). Policy changes to favor consumption of healthier foods have been limited, especially in low-income countries and greater policy research and action is required in this area (Hawkes et al., 2017; Farrell et al., 2021). To what extent can changes in retail food markets contribute to improved diets through informed choice or other means? As indicated, in low-income urban settings most fresh food is obtained from these markets. Choice of food purchases is complex and though price is a major driver (Smit, 2020), a range of strategies are involved in the often personalized way that preferred food is obtained from sellers, including via the "casero" system in Latin America (Alfaro, 2019, 2022). Farmers' markets, sometimes in combination with social and nutrition programs have taken advantage of such personalized buyer-seller relations to strengthen informed choice about healthy foods through nutrition information campaigns. Documentation of these activities mostly comes from the Global North (e.g., Dannefer et al., 2015; Hanson et al., 2022), but through personal experience of the authors they have also been observed in farmers' markets in the Global South. Direct interventions to improve the nutrition of vulnerable groups have also been undertaken through farmers' markets in the North through voucher systems, incentivising those groups to purchase healthy fresh food (Dannefer et al., 2015; Hanson et al., 2022). Voucher schemes have been used to stimulate consumption of healthy foods among vulnerable groups in the Global South by linking health facilities with agricultural producers (Cole et al., 2016) but not so far as we are aware through markets. It is suggested that drawing on the farmers' market experiences with nutrition education and voucher schemes in the North and on the health system-agriculture voucher schemes in the Global South, there is an investment need for research innovation on the role of retail food markets to contribute to increased nutrition knowledge and to be a partner in social programs to incentivize increased consumption of healthy food.

Recovering water and waste for the urban circular bioeconomy

By 2050, 80% of all food will be consumed on the 1–3% of global land area covered by towns and cities (Liu et al., 2014; Ellen MacArthur Foundation, 2019). The generation of large volumes of organic waste and wastewater within these hotspots poses a significant challenge, involving waste minimization and resource recovery and reuse to benefit the circular bioeconomy. Urban and peri-urban agriculture systems can absorb and benefit from food waste, either as feed for livestock or as organic fertilizer, and can create value from wastewater through irrigation. Of particular interest is the nutrient and energy rich fecal matter from on-site sanitation systems (septage) which are serving over 3 billion people globally (WHO and UNICEF, 2019). The opportunities are large, since less than 2% of the nutrients in the food entering urban areas are recovered from urban waste streams (Ellen MacArthur Foundation, 2019). However, wherever waste becomes an agricultural input, food safety is a key concern. For example, the farmland under planned irrigation with treated wastewater is globally at least 30 times smaller than the irrigated area exposed to untreated wastewater, indicating a significant hazard for public health (Drechsel et al., 2022). Based on a decade of research on the circular bioeconomy (Sally and Merrey, 2019), research investment priorities have to bridge between the perspectives of farmers in need of inputs, and the city with abundant waste, which might however not be safe for reuse.

From a (peri)urban *farmer perspective*, organic waste—mostly food waste in cities—offers a low-cost feed for livestock and an organic soil input for crops after waste composting. Both options have a long tradition and there is usually high demand, although this varies depending on quality (FAO, 2013). Municipal waste compost is often poor in nutrients and seldom a priority for farmers where manure or chemical fertilizer are available (Gaur and Singh, 1993). Farmers specialized in urban cash crops, such as leafy vegetables, depend on regular irrigation even in the rainy season. Unless there are enforced restrictions, crop and fish farmers accept any water source, including reliable (and often nutrient rich) wastewater, treated or not (WHO, 2006; Drechsel and Keraita, 2014; Amoah et al., 2021).

From a *city perspective*, waste collection, mostly over 50% organic in low- and middle-income countries, is a major expense (Kaza et al., 2018) and options like composting and feed use would reduce food waste and could also generate revenues from resource recovery (Otoo and Drechsel, 2018; Senanayake et al., 2021). However, use of food waste as feed can also be a biosafety risk, e.g., meat residuals transmitting foot and mouth disease unless the waste is well-processed (Salemdeeb et al., 2017). To improve the *quality* of municipal compost, an option is co-composting, e.g., with the proven safe use of nutrient-rich septage from onsite sanitation systems which can improve poor economic returns and enable scaling (Nikiema et al., 2014). Absence of cross-sectoral partnerships between public waste management and private fertilizer companies is another *scaling barrier*, resulting in poor marketing (Hoornweg et al., 1999). As a result, the often-postulated win–win situation where farmers in dire need of crop nutrients seize on urban waste compost remains so far, an exception (Drechsel, 2022). The opposite happens with respect to wastewater, which is usually a free resource, and its use is spreading quickly but in an unsafe manner, putting both farmers and consumers at risk. There have been significant efforts after the publication of WHO (2006) to develop multiple risk barriers from farm to fork (Amoah et al., 2011) but their *adoption remains very low* (Drechsel et al., 2022).

This situation calls for investments in research and innovation with respect to:

- Improved source segregation (separation of organic from non-organic waste) in households to benefit livestock farmers, business models to enhance the formal arrangements between food waste supply and demand by farmers, and improved farmer capacity in safe waste-processing to enhance biosafety (Jayathilake et al., 2022);
- The transformation into compost of food waste (not used as feedstock) for urban crop farmers, including location-specific financial and institutional business models and a supportive regulatory and financial environment to exploit research-based quality improvements and increase the viability and scale of municipal compost use (Lazurko et al., 2018);
- Research on innovative behavior change techniques, such as nudging (Barker et al., 2021), along the farm-to-fork contamination pathway, especially where risk awareness is low, to facilitate adaptation and scaling of research-based safety practices where the use of untreated wastewater in irrigation and aquaculture is common (Drechsel et al., 2022).

Innovating food systems planning and governance to support UPA

Where urban governments do actually address agriculture, it is commonly in terms of counterproductive modernist planning perspectives that deem urban food production inappropriate so that it is zoned out and often expressly prohibited. By contrast, where encouraged, as in Dar es Salaam and Kampala, urban food production systems are diverse and important, often including large-scale commercial operations using a range of technologies. They are by no means solely small-scale and subsistence-oriented (Lwasa et al., 2014, 2015). They also form important elements of urban green–blue infrastructure systems (Simon et al., 2021).

Effective, transparent governance is essential for coordinating and integrating the various activities and stakeholders involved in UPA as part of equitable and sustainable food systems. Land in and around cities used for growing food often traverses the boundaries of different local authorities with different priorities, powers, and resources. Collaboration is also required across multiple institutions in the public, private, and non-governmental sectors, with diverse sectoral jurisdictions, roles, resources, and powers, that seldom collaborate and often undervalue UPA. The need for governance innovations is underscored by the urgency of climate change and sustainability challenges, for which current boundaries and systems are often inappropriate, and, by extension, to promote achievement of Sustainable Development Goals 1, 2, 11, and 13 (United Nations, 2022).

Many countries lack appropriate national or regional legislation to support UPA and promote the circular agri-food economy. Local governments can, nevertheless, take important steps through integrated cross-sectoral planning and action on food production, marketing, and waste management, including resource recovery through municipal composting and feedstock use. Nevertheless, jurisdictional and spatial mismatches, along with inadequate political support, are common constraints worldwide (Simon, 2021; Treutwein and Langen, 2021).

Investing in institutional innovations for city-region food governance

The most appropriate scale for coherent planning, governance, and financing of urban food supply and security is now increasingly identified as the functional urban area or city region (Blay-Palmer et al., 2018; Cabannes and Marocchino, 2018; Acharya et al., 2020; Simon, 2021; Jayathilake et al., 2022; Prain, 2022). The city-region scale is most appropriate for addressing such disjunctures by providing an appropriate functional regional framing for integrated, multi-stakeholder agri-food policy and planning for a sustainable and resilient food system (Dubbeling et al., 2016, 2017; Blay-Palmer et al., 2018; Acharya et al., 2020).

In some contexts, such as China, city regions now have specific boundaries and dedicated governance systems (Wu, 2016) but more often they are functional and relational, focused—for purposes of this paper—on the food system (FAO RUAF Foundation, 2015; Karg et al., 2016; but see also Battersby and Watson, 2018). This does not imply that all foods can or must be produced locally; some mid-to long-distance transport of produce requiring larger areas for cultivation or different agro-ecological conditions will probably remain necessary. The delimitation of such regions might vary seasonally or for particular agro-commodity groups. This introduces governance challenges and requires institutional innovation to protect and boost production, enabling equitable, low emissions marketing, and promoting waste reuse. Investment is required to design and establish contextually appropriate institutional guidelines—including supportive "infrastructure" (Palmer et al., 2020), particularly as many stakeholders will not have experience of working together across the various types of boundary that may be encompassed by a city region. These guidelines should be co-produced through transdisciplinary, multisectoral participation based on mutual respect for diverse experience and expertise. The required research and investment would include inclusive procedures and rules, with appropriate facilitation to act as "honest broker" and to mediate the inevitably unequal power relations that often permeate such processes even when participants agree to appropriate principles of engagement (see Hemström et al., 2021; Simon, 2021; Prain, 2022, p. 55–56).

A crucial element of each specific context is the interface between such innovative horizontal governance processes and the vertical engagement by local governments with the strategic city region and higher levels of provincial and national government. For example, having an appropriate, urban-oriented national food system strategy can stimulate local action, as has happened in Kenya (Prain, 2022). For national policies to influence urban food systems, appropriate policy frameworks and multistakeholder cooperation needs to be in place at local level (Halliday et al., 2019).

Investing in geospatial innovations on urban food production and food deficits

Promoting sustainable and equitable urban food supply and security faces two challenges. First, urban and city-region food systems are diverse and fragmented, embracing formal, semi-formal, and informal components of different scales. Second, the systems are highly dynamic and subject to rapid change as a result of ongoing urban (re)development and land-use change. Low-income and informal producers on vestigial land pockets or using temporarily vacant land are particularly vulnerable. For these reasons and because many elements of the system may be deliberately concealed, investment in geospatial research is required to make these widely visible in order to gain a comprehensive and strategic overview and GIS database that can be updated regularly is a critical planning tool (Prain, 2022, p. 57–58).

In mapping the geographies of food production and consumption, identifying areas of food deficit and food deserts are important on equity grounds. This requires investment in secondary and primary data sourcing and analysis, including from social welfare programmes. For food production, the land use, irrigation, and harvest records require collation, but remotely sensed data will be essential, requiring both equipment—including use of drones and other innovative technologies—and capacity strengthening. Making food systems visible in this way could become a key step to making them more equitable and more sustainable, whilst taking steps to reduce the risk that this becomes a means of increasing control and taxation of hitherto unrecorded production.

Conclusions and recommendations

Growing populations, economic change, and climate change are putting great pressure on the natural, physical, and social resources of cities of the Global South and the ability of their food systems to feed urban populations appropriately. Furthermore, food waste management is a major concern of municipalities, and linear solutions are increasingly unsustainable. Circular waste flows could offer win–win opportunities for UPA and boost urban resilience. Building governance and planning structures for a greater recognition and integration of the food system within urban, peri-urban, and nearby rural spaces—the city-region food system—can help respond to many of these challenges.

The perspective articulated here is that opportunities exist for investing in innovations in different parts of the city-region food system that build on UPA research over recent decades (Yan et al., 2022) and can be adapted and scaled for greater urban

TABLE 1 Selected UPA research and innovation investment priorities.

Investment area	Research innovation needs	Policy, institutional, and financial innovation
Controlled Environment Agriculture (CEA)	CEA productivity and adaptation options especially in low-income contexts	Improved regulatory, financing, and incentives environment for protecting productive land and enabling CEA investments
Informal food markets	Mutually acceptable food safety and quality protocols (water, waste, hygiene, health)	Diversification of market functions, upgrading, and decentralization
Circular bioeconomy	Locally feasible safety protocols for waste reuse and incentive systems for their adoption	The enabling environment for the safe use of waste derived resources
Multi-stakeholder planning and governance	Visualizing the relevance of urban food systems	Horizontal and vertical linkages between stakeholders and sectors applying a city-region perspective

Source: Authors.

resilience, especially in the Global South. Table 1 summarizes key recommendations for investments in innovative research as well as policies and implementation options.

Boosting sustainable intensification of food production even on limited urban spaces is possible, e.g., through CEA, contributing to reduced resource use and urban emissions. For this and other UPA production systems, enabling policies and innovative start-up financing will be needed, as well as protecting peri-urban agricultural spaces through zoning and incentives policies, and designating and protecting urban public land areas for food production (Mougeot, 2000; Cabannes, 2015).

Informal food marketing is an essential but fragile component of the food system in the Global South. Innovative research and investment to reposition markets via participatory upgrading can increase food safety (including prevention of phytosanitary risks), equity, and efficiency. Market diversification to expand green marketing and reorient institutional markets toward local food procurement can generate nutrition, health, and climate change benefits. Investing in innovative partnerships between public health policy-making, nutrition services, and local food markets can also strengthen their contribution to healthier diets, food preparation, and hygiene.

A food systems perspective on organic waste can help cities become more resilient through moving toward circular bioeconomies. Urban and peri-urban agriculture can recover and reuse organic wastes in animal feed and composting and wastewater as a source of irrigation. Investments are needed in applied research to improve the quality and safety of the resources derived from waste and achieve the required behavior changes as well as effective public–private partnerships linking waste management and agriculture for scaling.

For city-region food systems to provide healthier food, decent employment, and reduced emissions, investment is needed in new types of food planning and governance. Food systems do not respect administrative boundaries, so more agile partnerships will be needed. These must be both horizontal—across the different multisectoral jurisdictions and interests of the city region where food production, distribution, and consumption occur—and vertical, to link with and influence national initiatives and strengthen cross-learning. Given that elements of the food system are often informal, invisible, and inequitable, mapping the geographies of production, distribution, and consumption can help make inequalities more visible and reduce vulnerabilities. A key investment should support cross-regional learning as there are high-potential examples that lend themselves to appropriate adaptation.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author/s.

Author contributions

The paper drew on two reports commissioned by the Commission on Sustainable Agricultural Intensification (CoSAI), on urban and investment opportunities for innovation in urban and peri-urban agriculture and in controlled environment agriculture, authored respectively by GP and JH. GP led the introduction, the section on markets, and the discussion. JH led the section on protecting productive land and boosting agricultural productivity. PD led the section on the circular bioeconomy and DS led the section on governance. All authors contributed reviews of all sections.

Acknowledgments

The authors acknowledge with appreciation the contribution to this paper of work on investment opportunities in innovations in urban and peri-urban agriculture and in controlled environment agriculture undertaken through the Commission on Sustainable Agricultural Intensification (CoSAI). We would also like to thank two reviewers of the paper and the paper editor for very helpful comments. We gratefully acknowledge all funding partners of the CGIAR Research Program on Water, Land and Ecosystems (WLE), and the One-CGIAR initiative on Resilient Cities through Sustainable Urban and Peri-urban Agri-Food Systems, who supported this research through their contributions to the CGIAR Fund (https://www.cgiar.org/funders/).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Acharya, G., Cassou, E., Jaffee, S., and Ludher, E. K. (2020). *RICH Food, Smart City*. Washington, DC: World Bank. doi: 10.1596/35137

Alfaro, A. M. H. (2019). *Encounters at Lima's Inner-City Marketplaces: Negotiating Fragmentation and Common Living in Urban Peru*. Doctoral dissertation, University College London, London. Available online at: https://discovery.ucl.ac.uk/id/eprint/10070259/1/AM%20Huaita%20Alfaro%202018%20PhD%20Dissertation%20-%20Final%20(e-thesis).pdf

Alfaro, A. M. H. (2022). "Lima markets beyond commerce: challenges and possibilities of common food spaces in periods of crisis," in *Marketplaces: Movements, Representations and Practices*, eds C. Sezer and R. van Melik (Oxon, UK: Routledge), 119–130.

Amoah, P., Gebrezgabher, S., and Drechsel, P. (2021). *Safe and Sustainable Business Models for Water Reuse in Aquaculture in Developing Countries*. Colombo: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). doi: 10.5337/2021.212

Amoah, P., Keraita, B., Akple, M., Drechsel, P., Abaidoo, R. C., and Konradsen, F. (2011). *Low-Cost Options for Reducing Consumer Health Risks from Farm to Fork Where Crops are Irrigated with Polluted Water in West Africa*. IWMI Research Report Series 141. Colombo: International Water Management Institute (IWMI). Available online at: http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB141/RR141.pdf

Arce, B., Prain, G., Valle, R., and Gonzales, N. (2007). Vegetable production systems as livelihood strategies in Lima-Peru: opportunities and risks for households and local governments. *ISHS Acta Horticult.* 762, 291–302. doi: 10.17660/ActaHortic.2007.762.28

Artemis (2020). *State of Indoor Farming*, 2020. Artemis. Available online at: https://artemisag.com/artemis-releases2020-state-of-indoor-farming-report/

Barker, H., Shaw, P. J., Richards, B., Clegg, Z., and Smith, D. (2021). What nudge techniques work for food waste behaviour change at the consumer level? A systematic review. *Sustainability* 13, 11099. doi: 10.3390/su131911099

Battersby, J., and Watson, V. (eds). (2018). *Urban Food Systems Governance and Poverty in African Cities*. London: Routledge. doi: 10.4324/9781315191195

Berdegué, J. A., Proctor, F. J., and Cazzuffi, C. (2014). *Inclusive Rural–Urban Linkages* (Working Paper Series No. 123). Santiago: Territorial Cohesion for Development Program, RIMISP.

Blay-Palmer, A., Santini, G., Dubbeling, M., Renting, H., Taguchi, M., and Giordano, T. (2018). Validating the city region food system approach: enacting inclusive, transformational city region food systems. *Sustainability* 10, 1680. doi: 10.3390/su10051680

Boossabong, P. (2018). "Articulating public agencies, experts, corporations, civil society and the informal sector in planning food systems in Bangkok," in *Integrating Food Into Urban Planning*, eds Y. Cabannes, and C. Marocchino (London; Rome: UCL Press and Food and Agriculture Organization of the United Nations), 60–79. doi: 10.2307/j.ctv513dv1.9

Brambila-Macias, J., Shankar, B., Capacci, S., Mazzocchi, M., Perez-Cueto, F. J., Verbeke, W., and Traill, W. B. (2011). Policy interventions to promote healthy eating: a review of what works, what does not, and what is promising. *Food Nutr. Bull.* 32, 365–375. doi: 10.1177/156482651103200408

Cabannes, Y. (2015). "Financing urban and peri-urban agriculture: what do we know, what should we know," in *Cities and Agriculture*, eds H. De Zeeuw and P. Drechsel (London: Routledge), 358–386.

Cabannes, Y., and Marocchino, C. (eds). (2018). *Integrating Food into Urban Planning*. London; Rome: UCL Press and Food and Agriculture Organization of the United Nations. doi: 10.2307/j.ctv513dv1

Cardoso, R. V. (2022). City-regional demographic composition and the fortunes of regional second cities. *Urban Geogr.* 1–23. doi: 10.1080/02723638.2022.2085436

Carus, M., and Dammer, L. (2018). The "circular bioeconomy"—concepts, opportunities, and limitations. *Ind. Biotechnol.* 14, 83–91 doi: 10.1089/ind.2018.29121.mca

Cole, D. C., Levin, C., Loechl, C., Thiele, G., Grant, F., Girard, A. W., et al. (2016). Planning an integrated agriculture and health program and designing its evaluation: experience from Western Kenya. *Eval. Program Plann.* 56, 11–22. doi: 10.1016/j.evalprogplan.2016.03.001

Community Land Trust Network (2022). *Community Land Trusts: Policy and Vision*. Available online at: https://www.communitylandtrusts.org.uk/policy-vision (accessed May 17, 2022).

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., and Leip, A. J. N. F. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* 2, 198–209. doi: 10.1038/s43016-021-00225-9

Crush, J., Havorka, A., and Tevera, D. (2011). Food security in Southern African cities: the place of urban agriculture. *Prog. Develop. Studies* 11, 285–305. doi: 10.1177/146499341001100402

Dannefer, R., Abrami, A., Rapoport, R., Sriphanlop, P., Sacks, R., and Johns, M. (2015). A mixed-methods evaluation of a SNAP-Ed farmers' market–based nutrition education program. *J. Nutr. Educ. Behav.* 47, 516–525. doi: 10.1016/j.jneb.2015.08.021

Davies, J., Hannah, C., Guido, Z., Zimmer, A., McCann, L., Battersby, J., and Evans, T. (2021). Barriers to urban agriculture in sub-Saharan Africa. *Food Policy* 103, 101999. doi: 10.1016/j.foodpol.2020.101999

Drechsel, P. (2022). Urban waste and agriculture: a win-win for farmers and for the city? *Urban Agric. Mag.* 38, 65–67.

Drechsel, P., and Keraita, B., (eds). (2014). *Irrigated Urban Vegetable Production in Ghana: Characteristics, Benefits and Risk Mitigation, 2nd Edn*. Colombo: International Water Management Institute (IWMI). doi: 10.5337/2014.219

Drechsel, P., Qadir, M., and Galibourg, D. (2022). The WHO guidelines for safe wastewater use in agriculture: a review of implementation challenges and possible solutions in the Global South. *Water* 14, 864. doi: 10.3390/w14060864

Dubbeling, M., Bucatariu, C., Santini, G., Vogt, C., and Eisenbeiß, K. (2016). *City Region Food Systems and Food Waste Management: Linking Urban and Rural Areas for Sustainable and Resilient Development*. Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, RUAF, Food and Agriculture Organization of the United Nations (FAO).

Dubbeling, M., Santini, G., Renting, H., Taguchi, M., Lançon, L., Zuluaga, J., et al. (2017). Assessing and planning sustainable city region food systems: insights from two Latin American cities. *Sustainability* 9, 1455. doi: 10.3390/su9081455

Ellen MacArthur Foundation (2019). *Cities and the Circular Economy for Food*. Ellen MacArthur Foundation (EMF). Available online at: https://ellenmacarthurfoundation.org/cities-and-circular-economy-for-food

Evans, D. L., Falagán, N., Hardman, C. A., Kourmpetli, S., Liu, S., Mead, B. R., and Davies, J. A. C. (2022). Ecosystem service delivery by urban agriculture and green infrastructure – a systematic review. *Ecosyst. Serv.* 54, 101405. doi: 10.1016/j.ecoser.2022.101405

FAO (2013). *Toolkit – Reducing the Food Wastage Footprint*. Rome: FAO.

FAO (2019). *FAO Framework for the Urban Food Agenda*. Rome: FAO.

FAO and RUAF Foundation (2015). *A Vision for City Region Food Systems: Building Sustainable and Resilient City Regions*. Rome: Food and Agriculture

Organization of the United Nations. Available online at: http://www.fao.org/3/a-i4789e.pdf

Farrell, P., Rachmi, C. N., Mulcahy, G., Helble, M., and Thow, A. M. (2021). Food environment research is needed to improve nutrition and wellbeing in the Asia and the Pacific region. *Public Health Nutr.* 24, 4706–4710. doi: 10.1017/S136898002100241X

Foeken, D. W. J. (2004). *Urban Agriculture in East Africa as a Tool for Poverty Reduction: A Legal and Policy Dilemma?* (ASC Working Paper Series No. 65). Leiden: African Studies Center (ASC).

Freudenberg, N. (2016). Healthy-food procurement: using the public plate to reduce food insecurity and diet-related diseases. *Lancet Diabetes Endocrinol.* 4, 383–384. doi: 10.1016/S2213-8587(16)00078-4

Gaur, A. C., and Singh, G. (1993). *Role of Integrated Plant Nutrient Systems in Sustainable and Environmentally Sound Agricultural Development*. RAPA Publication: 1993/13, 110–130. Bangkok: FAO.

Giroux, S., Blekking, J., Waldman, K., Resnick, D., and Fobi, D. (2021). Informal vendors and food systems planning in an emerging African city. *Food Policy*, 103, 101997. doi: 10.1016/j.foodpol.2020.101997

Global Nutrition Report (2020). *2020 Global Nutrition Report: Action on Equity to End Malnutrition*. Bristol: Development Initiatives. Available online at: https://globalnutritionreport.org/reports/2020-global-nutrition-report

Grace, D. (2015). Food safety in low and middle income countries. *Int. J. Environ. Res. Public Health* 12, 10490–10507. doi: 10.3390/ijerph120910490

Halliday, J., Platenkamp, L., and Nicolarea, Y. (2019). *A Menu of Actions to Shape Urban Food Environments for Improved Nutrition, GAIN, MUFPP and RUAF*. Available online at: https://foodactioncities.org/app/uploads/2021/06/LCS4_Surabaya_Multi-Stakeholder_Forum.pdf

Halliday, J., von Kaufmann, R., and Herath, K. V. (2021). *An Assessment of Controlled Environment Agriculture (CEA) in Low- and Lower-Middle Income Countries in Asia and Africa, and its Potential Contribution to Sustainable Development*. Colombo: Commission on Sustainable Agriculture Intensification. CGIAR Research Program on Water, Land and Ecosystems (WLE).

Hanson, K. L., Meng, X., Volpe, L. C., Jilcott Pitts, S., Bravo, Y., Tiffany, J., and Seguin-Fowler, R. A. (2022). Farmers' market nutrition program educational events are broadly accepted and may increase knowledge, self-efficacy and behavioral intentions. *Nutrients* 14, 436. doi: 10.3390/nu1403 0436

Hawkes, C., Harris, J., and Gillespie, S. (2017). "Changing diets – urbanisation and the nutrition transition," in *2017 Global Food Policy Report* (Washington, DC: International Food Policy Research Institute), 34–41.

Hemström, H., Simon, D., Palmer, H., Perry, B., and Polk, M. (2021). *Transdisciplinary Knowledge Co-production: A Guide for Sustainable Cities*. Rugby: Practical Action Publishing. Available online at: https://practicalactionpublishing.com/book/2544/transdisciplinary-knowledge-co-production-for-sustainable-cities

Hertel, T., Elouafi, I., Tanticharoen, M., and Ewert, F. (2021). Diversification for enhanced food systems resilience. *Nat. Food* 2, 832–834. doi: 10.1038/s43016-021-00403-9

Hoornweg, D., Thomas, L., and Otten, L. (1999). *Composting and its Applicability in Developing Countries, Urban Waste Management, Working Paper Series No. 8*. Washington, DC: World Bank, Urban Development Division.

ILO (2018). *Women and Men in the Informal Economy: A Statistical Picture*. Geneva: International Labor Office, International Labour Organization.

IPES-Food (2017). What *Makes Urban Food Policy Happen*? *Insights from Five Case Studies*. International Panel of Experts on Sustainable Food Systems.

Jayathilake, N., Aheeyar, M., and Drechsel, P. (2022). Food waste to livestock feed: prospects and challenges for swine farming in periurban Sri Lanka. *Circ. Econ. Sust*. 2022, 1–15. doi: 10.1007/s43615-022-00168-8

Jensen, M. (2002). Controlled environment agriculture in deserts, tropics and temperate regions – a world review. *Acta Hortic.* 578, 19–25. doi: 10.17660/ActaHortic.2002.578.1

Karg, H., Drechsel, P., Akoto-Danso, E. K., Glaser, R., Nyarko, G., and Buerkert, A. (2016). Foodsheds and city region food systems in two West African cities. *Sustainability* 8, 1175. doi: 10.3390/su8121175

Kaza, S., Yao, L. C., Bhada-Tata, P., and Van Woerden, F. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank. doi: 10.1596/978-1-4648-1329-0

Kelly, S., and Swensson, L. F. J. (2017). *Leveraging Institutional Food Procurement for Linking Small Farmers to Markets: Findings from WFP's Purchase for Progress Initiative and Brazil's Food Procurement Programmes*. FAO Agricultural Development Economics Technical Study 1. Rome: FAO, p. 101.

Kriewald, S., Pradhan, P., Costa, L., Ros, A. G. C., and Kropp, J. P. (2019). Hungry cities: how local food self-sufficiency relates to climate change, diets, and urbanization. *Environ. Res. Lett.* 14, 094007. doi: 10.1088/1748-9326/ab2d56

Lazurko, A., Drechsel, P., and Hanjra, M. A. (2018). *Financing Resource Recovery and Reuse in Developing and Emerging Economies: Enabling Environment, Financing Sources and Cost Recovery*. Colombo: IWMI/WLE. doi: 10.5337/2018.220

Lestikow, G., MacArthur, J., Chowdhury, R., Davis, J., and Wei, Y. (2017). *Integrating WASH and Nutrition in Market-Based Interventions: Principles and Results from the Field.* Available online at: https://repository.lboro.ac.uk/articles/conference_contribution/Integrating_WASH_and_nutrition_in_market-based_interventions_principles_and_results_from_the_field/9589184/files/17228270.pdf

Liu, Z., He, C., Zhou, Y., and Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landsc. Ecol.* 29, 763–771. doi: 10.1007/s10980-014-0034-y

Lwasa, S., Mugagga, F., Wahab, B., Simon, D., Connors, J., and Griffith, C. (2014). Urban and peri-urban agriculture and forestry: transcending poverty alleviation to climate change mitigation and adaptation. *Urb. Clim.* 7, 92–106. doi: 10.1016/j.uclim.2013.10.007

Lwasa, S., Mugagga, F., Wahab, B., Simon, D., Connors, J., and Griffith, C. (2015). A meta-analysis of urban and peri-urban agriculture and forestry in mediating climate change. *Curr. Opin. Environ. Sust*. 13, 68–73. doi: 10.1016/j.cosust.2015.02.003

Malec, R., Sanitini, G., and Haliday, J. (2022). Defining resilience to multiple shocks and stresses in the context of city region food systems. *Urban Agr. Mag.* 38, 13–15.

Marocchino, C. (2009). *A Guide to Upgrading Rural Agricultural Retail Markets*. Italy: Food and Agriculture Organization of the United Nations.

Mougeot, L. (2000). *Urban Agriculture: Definition, Presence, Potentials and Risks, and Policy Challenges*. IDRC Cities Feeding People Series Report 31, 58.

Mytton-Mills, H. (2018). "Controlled environment agriculture: what is it, and how is it applied?," in ed Kaufmann, *Special Issue on Controlled Environment Agriculture (CEA), Agriculture for Development No. 34, Summer 2018*. Tropical Agriculture Association.

Nikiema, J., Cofie, O. O., and Impraim, R. (2014). *Technological Options for Safe Resource Recovery from Fecal Sludge. Resource Recovery and Reuse Series 2*. Colombo: International Water Management Institute (IWMI). doi: 10.5337/2014.228

Open Access Government (2022) *COVID-19 Originated at Wuhan Wet Market via Raccoon, Dogs and Foxes*. Available online at: https://www.openaccessgovernment.org/covid-19-originated-at-wuhan-wet-market-via-raccoon-dogs-and-foxes/140578/ (29 July, 2022).

Otoo, M., and Drechsel, P. (2018). *Resource Recovery from Waste: Business Models for Energy, Nutrient and Water Reuse in Low- and Middle-income Countries*. Routledge. Availabe online at: https://cgspace.cgiar.org/handle/10568/93011

Palmer, H., Polk, M., Simon, D., and Hansson, S. (2020). Evaluative and enabling infrastructures: supporting the ability of urban co-production processes to contribute to societal change. *Urb. Transform.* 2, 6. doi: 10.1186/s42854-020-00010-0

Pinstrup-Andersen, P. (2018). Is it time to take vertical indoor farming seriously? *Glob. Food Secur.* 17, 23–235. doi: 10.1016/j.gfs.2017.09.002

Popkin, B. M., Adair, L. S., and Ng, S. W. (2012). Global nutrition transition and the pandemic of obesity in developing countries. *Nutr. Rev*. 70, 3–21. doi: 10.1111/j.1753-4887.2011.00456.x

Prain, G. (2010). "The institutional and regional context," in *African Urban Harvest*, eds G. Prain, N. Karanja, and D. Lee-Smith (New York, NY: Springer), 1–12. doi: 10.1007/978-1-4419-6250-8_1

Prain, G. (2022). *Potential of Urban and Peri-urban Agriculture in the Global South: Identifying Innovations for Future Investments*. Commission on Sustainable Agricultural Intensification (CoSAI). Available online at: https://hdl.handle.net/10568/119438

Salemdeeb, R., Erasmus, K. H. J., Zu Ermgassen, E. K. H. J., Kim, M., Balmford, A., and Al-Tabb, A. (2017). Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. *J. Clean. Prod.* 140, 871–880. doi: 10.1016/j.jclepro.2016.05.049

Sally, H., and Merrey, D. (2019). *Outcome evaluation of research for development work conducted in Ghana and Sri Lanka under the Resource, Recovery and Reuse (RRR) subprogram of the CGIAR Research Program on Water, Land and Ecosystems (WLE)*. IWMI, WLE. Available online at: https://cgspace.cgiar.org/handle/10568/107242

Santandreu, A. (2018). "Urban agriculture in Lima metropolitan area: one (short) step forward, two steps backwards – the limits of urban food planning," in *Integrating Food into Urban Planning*, eds Y. Cabannes and C. Marocchino (London; Rome: UCL Press and the Food and Agriculture Organization of the United Nations), 117–133. doi: 10.2307/j.ctv513dv1.12

Schreiber, K., Hickey, G. M., Metson, G. S., Robinson, B. E., and MacDonald, G. K. (2021). Quantifying the foodshed: a systematic review of urban food flow and local food self-sufficiency research. *Environ. Res. Lett.* 16, 023003. doi: 10.1088/1748-9326/abad59

Senanayake, D., Reitemeier, M., Thiel, F., and Drechsel, P. (2021). "Business models for urban food waste prevention, redistribution, recovery and recycling," in *CGIAR Research Program on Water, Land and Ecosystems (WLE). (Resource Recovery and Reuse Series 19)* (Colombo: International Water Management Institute (IWMI)). doi: 10.5337/2021.208

Sharpe, T., Muragijimana, C., and Thomas, E. (2019). Product design supporting improved water, sanitation, and energy services delivery in low-income settings. *Sustainability* 11, 6717. doi: 10.3390/su11236717

Siebert, M., and Mbise, A. (2018). *Toilets Not Taxes: Gender Inequity in Dar es Salaam's City Markets*. ICTD Working Paper 89 Institute of Development Studies, November 2018, Brighton, UK.

Simon, D. (2021). Co-productive tools for transcending the divide: building urban–rural partnerships in the spirit of the new Leipzig Charter. *Land* 10, 894. doi: 10.3390/land10090894

Simon, D., Goodness, J., Puppim de Oliviera, J., Macedo, L. M., Lwasa, S., Hermansson Török, E., and Elmqvist, T. (2021). "Urban governance of and for urban green and blue infrastructure," in *Urban Ecology in the Global South*, eds C. Shackleton, S. Cilliers, E. Davoren, and M. du Toit (Cham: Springer), 403–431. doi: 10.1007/978-3-030-67650-6_16

Smit, W. (2020). "The food environment and health in African cities: analyzing the linkages and exploring possibilities for improving health and wellbeing," in *Urban Transformations and Public Health in the Emergent City,* eds M. Keith and A. A. de Souza Santos (Manchester, UK: Manchester University Press), 123–146.

Song, L., and Taylor, J. (2018). "Making food markets work. Towards Participatory planning and adaptive governance," in *Integrating Food into Urban Planning*, eds Y. Cabannes and C. Marocchino (London; Rome: UCL Press and Food and Agriculture Organization of the United Nations).

Swensson, L. F., Hunter, D., Schneider, S., and Tartanac, F. (2021). Public food procurement as a game changer for food system transformation. *Lancet Planet Health* 5, e495–e496. doi: 10.1016/S2542-5196(21)00176-5

Taylor, J. R. (2020). Modeling the potential productivity of urban agriculture and its impacts on soil quality through experimental research on scale-appropriate systems. *Front. Sustain. Food Syst.* 4, 89. doi: 10.3389/fsufs.2020.00089

Treutwein, R., and Langen, N. (2021). Setting the agenda for food waste preventionŰA perspective on local government policymaking. *J. Clean. Prod.* 286, 125337. doi: 10.1016/j.jclepro.2020.125337

UNEP (2021). *Food Waste Index Report, 2021*. Nairobi: United Nations Environment Program, UNEP.

UN-Habitat (2020). World Cities Report 2020: The *Value* of *Sustainable Urbanization*. Nairobi: UN-Habitat.

United Nations (2022). *The Sustainable Development Goals Report 2022*. New York, NY: United Nations.

Vilar-Compte, M., Burrola-Méndez, S., Lozano-Marrufo, A., Ferré-Eguiluz, I., Flores, D., Gaitán-Rossi, P., et al. (2021). Urban poverty and nutrition challenges associated with accessibility to a healthy diet: a global systematic literature review. *Int. J. Equity Health* 20, 1–19. doi: 10.1186/s12939-020-01330-0

Vittersø, G., Torjusen, H., Laitala, K., Tocco, B., Biasini, B., Csillag, P., et al. (2019). Short food supply chains and their contributions to sustainability: participants' views and perceptions from 12 European cases. *Sustainability* 11, 4800. doi: 10.3390/su11174800

von Kaufmann, R., editor. (2018). *Special issue on Controlled Environment Agriculture (CEA), Agriculture for Development No. 34, Summer 2018*. Tropical Agriculture Association.

WHO (2006). *Guidelines of the Safe Use of Wastewater, Excreta and Grey Water, Vol. 2, Wastewater Use in Agriculture*. World Health Organization (WHO).

WHO and UNICEF (2019). *Progress on household drinking water, sanitation and hygiene 2000-2017: Special focus on inequalities*. New York: World Health Organization (WHO) and United Nations Children's Fund (UNICEF). Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP).

Wu, F. (2016). China's emergent city-region governance: a new form of state spatial selectivity through state-orchestrated rescaling. *Int. J. Urb. Region. Res.* 40, 1134–1151. doi: 10.1111/1468-2427.12437

WUWM (2021). *Conference Report 2021, World Union of Wholesale Markets*. Hague: WUWM. Available online at: https://wuwm.org/wp-content/uploads/2021/09/WUWM_2021_Conference_Report.pdf

Yan, D., Liu, L., Liu, X., Zhang, M. (2022). Global trends in urban agriculture research: a pathway toward urban resilience and sustainability. *Land* 11, 117. doi: 10.3390/land11010117

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 01 December 2022
DOI 10.3389/fsufs.2022.1014691

Check for updates

OPEN ACCESS

EDITED BY
P. V. Vara Prasad,
Kansas State University, United States

REVIEWED BY
Christopher Miles,
Cornell University, United States
Henry Jordaan,
University of the Free State,
South Africa

*CORRESPONDENCE
Apoorve Khandelwal
apoorve.khandelwal@ceew.in

SPECIALTY SECTION
This article was submitted to
Land, Livelihoods and Food Security,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 08 August 2022
ACCEPTED 28 October 2022
PUBLISHED 01 December 2022

CITATION
Khandelwal A, Agarwal N, Jain B,
Gupta D, John AT and Farah Cox P
(2022) Scaling up sustainability
through new product categories and
certification: Two cases from India.
Front. Sustain. Food Syst. 6:1014691.
doi: 10.3389/fsufs.2022.1014691

Scaling up sustainability through new product categories and certification: Two cases from India

Apoorve Khandelwal[1]*, Nandini Agarwal[1], Bhamini Jain[1], Darshna Gupta[1], Anjaly Teresa John[1] and Paul Farah Cox[2]

[1]Council on Energy, Environment and Water, New Delhi, India, [2]Scriptoria Ltd., London, United Kingdom

Introduction: The Indian food system faces a nexus of challenges in supply, demand and market linkages in the face of environmental and human development needs. The current agri-food system demands large-scale sustainable innovations, facilitated by an action-oriented approach by the rising number of actors in the agricultural space. These actors include public, private, non-profit and research institutions. They increase the scope for innovations to emerge and scale up through refocused investments and novel collaborations. Such successes in India, furthermore, can provide models of promising innovation pathways for many other countries in the Global South. Yet few case studies are available on successful innovations that have gone beyond the longstanding technology-led approach.

Methods (case study methods): This article presents two cases of other pathways. The first is an example of a differentiated new product category: the "pesticide-free" food product category and dedicated value chain established by Safe Harvest Private Limited. The second is an example of self-regulation through a certification standard: the Trustea code created within the Indian domestic tea industry.

Results: Both are driving sustainability at scale in Indian agri-food systems in two very different contexts, with the private sector leading the way.

Discussion: They offer insights on the roles of end users, trust, informal and formal links and actions, government endorsement, innovation bundling, and partnership.

KEYWORDS

scaling, innovation, product differentiation, certification, standards, pesticide-free, value-chain development, India

Introduction

Since the Green Revolution hit India, productivity-raising agricultural innovations have transformed agri-food systems, and 92% of these have been technological solutions such as high-yielding crop varieties and chemical fertilizers. The focus of the Green Revolution was on increasing production and commodity specialization, supported by government policies. Currently, however, India is experiencing productivity stagnation; the technological approaches of the past face challenges in improving productivity further while also accounting for environmental and social needs (Singh, 2004). The small and marginal farmers who make up the largest share of country's agrarian economy are facing serious livelihood risks, exacerbated by rising income inequalities and a steep increase in their seasonal vulnerability due to the impacts of climate change. Input-intensive production that focuses on monocultures is not proving resilient to either socioeconomic or climatic shocks.

The opportunities for innovation in India's agri-food systems lie in the nexus of these challenges. Change is coming, and farmers need more support to move from high-input conventional cropping to innovative sustainable practices. The report *Sustainable Agriculture in India 2021* (Gupta et al., 2021) shows that there is a dearth of transitional support to farmers as they shift from conventional practices to low-input sustainable practices—and farmers require such support to cope with the initial income loss risks and develop new capacities. There are limited incentives from the market such as price premiums, and implements are not widely available to reduce the labor costs of weeding and residue management. Farmers who already engage in sustainable practices do not have access and connections to appropriate markets. To make matters worse, the public incentive structure actively discourages the transition to sustainable agriculture. The government allocated half of the Ministry of Agriculture's INR 142,000 crore (USD 19.2 billion[1]) budget to subsidize chemical fertilizers in 2021, while allocating just 0.8% to the flagship National Mission for Sustainable Agriculture (Gupta et al., 2021). Furthermore, half a century of focus on irrigated regions has limited investment and innovation in the other 55% of India's net sown area.

All of the above has maintained the prevalence of practices—such as indiscriminate use of pesticides—that do not necessarily improve productivity, but have severe repercussions on profitability, the environment and human health (Bhardwaj and Sharma, 2013; Shetty et al., 2014; Sharma and Singhvi, 2017). The uptake of sustainable agri-food practices and systems remains low. Of the 16 sustainable practices and systems studied by Gupta et al. (2021), only six had been scaled up beyond 5% of the net sown area and/or 4% of the farmers in India. In descending scale these are crop rotation, agroforestry, rainwater harvesting, mulching, precision farming, and integrated pest management.

Nevertheless, a patchwork of interesting experiments and initiatives are appearing around India to enable the introduction and scaling of more sustainable innovations. An encouraging rise in the number of actors in the agricultural space—from among public, private, non-profit, and research institutions—is multiplying the possibilities to broker innovation networks (World Bank, 2012; Moschitz et al., 2015; Saravanan and Suchiradipta, 2017). There has always been strong *potential* for innovation in these systems, but its *feasibility* at scale is only emerging with the increasing number and diversity of actors. Repurposing investments can further build and expand the scope of this innovation—spurring transitions to more socio-ecologically resilient pathways.

Recognizing this, the Commission on Sustainable Agriculture Intensification (CoSAI) initiated a series of country studies with India, Brazil and Kenya, for documenting notable innovation pathways in sustainable agri-food systems (Chiodi Bachion et al., 2022; Khandelwal et al., 2022; Mati et al., 2022). The studies used a shared analytical framework to generate lessons on factors leading to successful innovation pathways, aiming to guide future investment. Successes in India can thus provide models of promising pathways for many other countries to follow in the Global South.

In the past there have been few case studies generated on successful innovations that have driven sustainability at scale in Indian agri-food systems. The available ones generally fall short of providing transferrable insights to innovation managers, investors, and other stakeholders around the world seeking to instigate large-scale innovation. Among others, models are lacking that fulfill the promises of product differentiation through new product categories, and of industry-led standards and certification in domestic markets of the Global South. This study presents two such cases that are driving sustainability in agri-food systems in two very different contexts, with the private sector leading the way. It focuses on the scaling up of non-pesticide management pursued by Safe Harvest Private Limited through its "pesticide-free" product category; and the Trustea standard and certification effort in Indian tea production.

Materials and methods

The innovation pathway studies undertaken across India (Khandelwal et al., 2022), Brazil (Chiodi Bachion et al., 2022), and Kenya (Mati et al., 2022) used a common investigative approach and analytical framework co-developed by CoSAI and the country partners. In India, we created a list of potential cases based on web searches, and complemented this with additional suggestions sourced from partner organizations of the Council on Energy, Environment and Water working on the topic of sustainable agri-food systems. We considered the following definition of innovation while identifying these cases:

- An innovation is an intervention or a bundle of interventions that have created a long-lasting, measurable, and transformative change.
- The change should be reflected as a positive impact on social, economic, and/or environmental dimensions.
- The intervention(s) may be in areas inclusive of, but not limited to, technology, finance, institutional structures, governance, policy, and business.
- Innovation is not necessarily a novel idea; it can also refer to an old idea that has been applied in a new way.

1 Approximate exchange rate: USD 1 = INR 73.81 in 2021.

- A successful innovation is the one that has scaled up significantly in the given context.

The master list was screened for sufficient availability of data, scale achieved, evidence of transformational change, financial sustainability, and representation of a variety of farms and farmers in diverse agro-ecological zones. We selected three cases for analysis. While the first of these was the case of Andhra Pradesh Community Managed Natural Farming (detailed in Khandelwal et al., 2022), we devote this paper to the two private-sector-driven cases of Safe Harvest Private Limited and Trustea.

The objective of the case study process was to capture the key takeaways from each of the cases: practical, evidence-based lessons on factors that influence success in innovation pathways for sustainable agri-food systems. The analytical approach was based on developing and analyzing a theory of change (considering factors inside and outside the scope of influence of innovation actors, that affect the results of an intervention) for each case (Figure 1), based on relevant literature on the selected cases and detailed interviews with key informants. The literature consisted of documents available from the case websites as well as independent research papers where available. The primary informants were identified through this literature, and a snowball sampling method was used to identify others. We sought out independent case experts to triangulate research findings, and ensure presentation of unbiased analysis. Beyond the theory of change, each case was analyzed using a question shared across the three country studies: *In your opinion, justified by evidence, what role did the following factors play in explaining the outcome at scale?*

- The innovation processes.
- Innovation characteristics, including business/delivery/funding models.
- Relevance to demand, needs, and priorities of users, other stakeholders.
- Characteristics of the users or places, e.g., infrastructure, education.
- Context, e.g., policy enabling environment, public sector organizations and capacity, value chain or market system actors.
- Choice of scaling pathway and strategy.
- Specific scaling activities, e.g., evidence generation, advocacy/marketing, community engagement, pricing, risk mitigation, use of champions.
- Characteristics of organizations/actors leading or driving the innovation and scaling process.
- Characteristics of partnerships and the organizations/actors that served as partners in the innovation and scaling process.

Due to the COVID-19 pandemic, we conducted all interviews online or over the telephone, holding multiple interviews with individual stakeholders to compensate for the lack of physical interaction. Given the snowball sampling method we adopted to conduct the key informant interviews, interviewees were largely limited to contacts shared by the key stakeholders or drivers of Safe Harvest and Trustea. It was not in the scope of the study to interview end users, such as customers of Safe Harvest or its farmers.

Results

Safe Harvest

Safe Harvest Private Limited is a triple bottom line company based in Bengaluru that retails "pesticide-free" food, backed up by publicly available records of its product testing for chemical residues. Under the triple bottom line concept, it is committed to measuring its social and environmental impact on profit, people, and planet. It was the first business in India to retail products in the "pesticide-free" product category, where agricultural produce is grown under non-pesticide management. It also introduced a "zero certification" mark on its products signals the differentiation of its offerings.

Safe Harvest directly sources non-pesticide-managed produce including lentils, beans, whole-grain cereals and flours, millets, spices, herbs, sugar, and other sweeteners from farmer producer organizations (FPOs) situated across 12 states of India. FPOs are legal entities composed of primary producers who share in profits; it is an umbrella term for farmer producer companies, cooperatives, and societies. Partner FPOs connect Safe Harvest to more than 100,000 farmers. Most of these are small and marginal farmers, and close to 2,500 are tribal farmers (Safe Harvest interviews).

Safe Harvest understands non-pesticide management as something economically viable and practical for small and marginal farmers in India, as opposed to organic farming, where farmers would also need to give up chemical fertilizers. Most small and marginal farmers cultivate low-fertility soils and cannot give up chemical fertilizers without a yield dip in the transition period that comes with a complete phase-out of chemical inputs. On the other hand, it is chemical pesticides that have the most immediate and hazardous impacts on human health—especially on farmers, who have direct contact—and the ecosystem (Bhardwaj and Sharma, 2013; Sharma and Singhvi, 2017). Transitioning out of these was a more accessible path that would not necessarily demand compromising on yields and productivity. In fact, much of Safe Harvest's demographic of farmers were already farming with minimal or no chemical pesticides, as these inputs were not affordable, accessible, and available to them. Non-pesticide management was thus a highly viable and scalable option for these farmers, compared with totally organic farming practices.

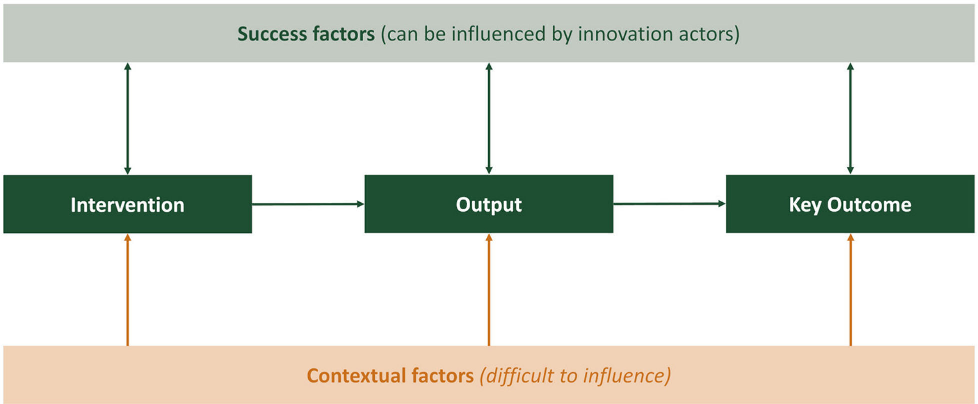


FIGURE 1
A modified version of the results chain, which additionally shows how various factors, inside or outside the scope of the influence of innovation actors, affect the results of an intervention.

The partner FPOs promote and adhere to non-pesticide management practices among their members. Safe Harvest ensures the absence of chemical pesticide residues and adulterants via rigorous testing during the storing, cleaning, and value-addition processes of its consumer food products. The company works via a farm-to-kitchen model (Figure 2), making its products available at a price point that is only 10%—20% higher than conventional branded food products at large retailers across India—both brick-and-mortar stores and popular e-commerce platforms such as Flipkart and Big Basket (interview with leadership at Safe Harvest, October 2, 2021). This taps into that sub-segment of the middle-income consumer market where there is awareness of and demand for "pesticide-free" foods for health and safety.

History of Safe Harvest

Grassroots beginnings

Experimentation with the Safe Harvest business model began in 2005, when eight NGOs who had been working with agricultural communities and environmental sustainability at the grassroots level founded the Non-Pesticide Management (NPM) Network with funding from the Ford Foundation. This initial grant was essential for the NPM Network members to pilot their ideas for the Safe Harvest model, deepen their understanding of non-pesticide management practices, build their collaborative capacities, develop the capacities of their partner FPOs, and align their long-term visions in the process. In 2009, Safe Harvest was registered as a for-profit company to address the goal of bridging market access for "pesticide-free" produce for small and marginal farmers.

As Safe Harvest emerged from grassroots work with agricultural communities, its services were rooted in the needs and the priorities of these communities. It built on the existing non-pesticide management practices of the farmers to build a new product category, a well-controlled supply chain, and a market for their products. The "pesticide-free" category solved issues associated with organic cultivation on both ends: the costs of transition and certification for farmers; and the affordability of products to price-sensitive middle-income consumers, who were excluded from the higher pricing of the organic market.

Working with farmer producer organizations

Safe Harvest also built on the rising level of farmer collectivization in India. However, farmer collectivization is still evolving in the country and the necessary ecosystem to adequately support FPOs is in development. FPOs require special support in their early years, with NABARD (2020) reporting that the "majority of these FPOs are in the nascent stage of their operations with shareholder membership ranging from 100 to over 1,000 farmers and [they] require not only technical hand-holding support but also adequate capital and infrastructure facilities, including market linkages for sustaining their business operations." Still, Safe Harvest decided to establish business relationships at the FPO level instead of procuring produce from individual farmers. The company understood the limits faced by small and marginal farmers and the need for collective efforts, particularly considering issues around pesticide cross-contamination from neighboring fields. Additionally, each farmer's limited marketable surplus alone would be very difficult to bring into the organized bulk and retail markets.

At the same time, the relationships with FPOs were more than purely transactional. Safe Harvest had a long-term perspective on nurturing trust. This ensured sustainability in the relationships, encouraged buy-in by farmers and FPOs, helped them endure through times of conflict, and enabled Safe Harvest to support FPO development through the NPM Network. FPOs

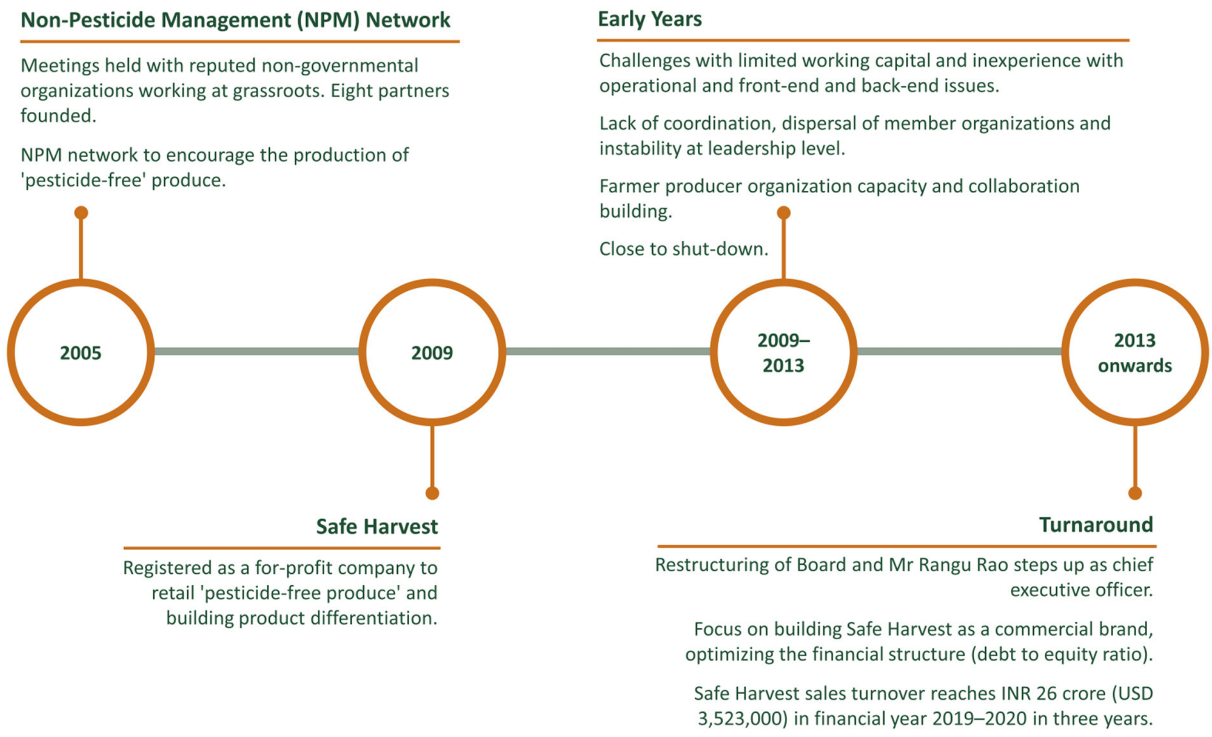


FIGURE 2
Timeline of key events in Safe Harvest.

were not contractually barred from selling to other buyers, and when Safe Harvest had to pause a relationship because the output did not pass residue testing, they could still return to the FBO the following year. Because the company grew out of NGO roots, it was guided by an effort to build a pan-Indian non-pesticide management movement committed to food safety and farmer access. It ensured training of FPOs on market preparedness, value addition, aggregation, and storage, building up its supply chain partners—while also explicitly building up the bargaining power of small, marginal and tribal farmers.

Value chain and consumer base development

When Safe Harvest first came into the market, there was no pre-existing supply chain specifically designed for retailing "pesticide-free" products, so there were myriad risks of cross-contamination. Furthermore, there was limited consumer awareness—not only of its brand and products, but more generally of non-pesticide management, and of the importance of testing and evidencing claims on food products. Safe Harvest had limited working capital, it lacked experience engaging with the market, and almost all of its FPO partners were accessing organized markets for the first time (Anil, 2019). In a highly competitive market, maintaining relatively affordable pricing and ensuring product availability were steep challenges. In 2012 and 2013, Safe Harvest was close to shutting down (see Figure 3).

However, post-2013, it experienced a turnaround. The company internally restructured its board and Rangu Rao, a founding member of the non-pesticide management movement and Safe Harvest, stepped up as the CEO. The focus shifted to building Safe Harvest as a commercial brand, optimizing the financial structure in its debt-to-equity ratio, and ensuring market differentiation for "pesticide-free" products, including generating evidence to support the claim for differentiation. Safe Harvest transitioned from its NGO approach to operating as a commercial social enterprise, while retaining its mission-driven approach—which was key in defining how it built relationships, what processes it engaged with, how it formulated solutions, and where it looked for funding partners.

Commercial success

In 2016, it received institutional funding in both debt and equity. Safe Harvest has since garnered traction among consumers for its products, with sales turnover reaching INR 26 crore (USD 3.5 million) in financial year 2019–20 (Safe Harvest interviews). It built its early customer base in South India, where it observed a strong initial awareness around food safety. It was then able to build its presence as this awareness spread across the country—especially in light of the COVID-19 pandemic and increased consumer concern for health and food safety. In 2019–20 its sales territories were limited to Chennai, Bengaluru,

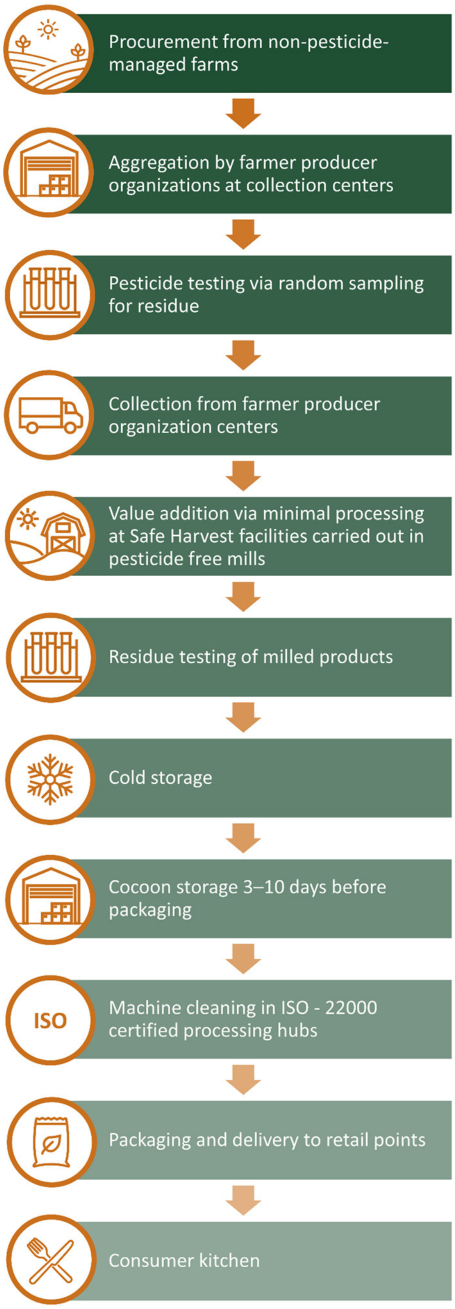


FIGURE 3
Safe Harvest's flow of a farm-to-kitchen model. Authors' creation based on Safe Harvest website, inputs from interviews and Anil (2019).

Hyderabad, Visakhapatnam, and Vijayawada, but this has since expanded to include the National Capital Region, Mumbai, and Pune.

Rather than investing in advertising through newspapers, billboards, or television (which the company lacked the funds to pursue), Safe Harvest used its on-shelf product availability, selection, and "zero certification" mark to register its presence in multiple product categories. According to its financial reports, 15%–20% of its revenue is invested in marketing and distribution. Its communication and sales teams also work closely on social media and direct consumer outreach (Anil, 2019). Consumers are offered discounts through brick-and-mortar retail chains and e-commerce platforms, and the visibility of Safe Harvest on these platforms is rising. As of 2021, Safe Harvest was working on making the "zero certification" on its packaging traceable.

Safe Harvest's innovation

Launching a new product category

The core innovation at Safe Harvest was the creation of a new product category, "pesticide-free" food, and a specialized supply chain for it. Before this, the existing product categories were organic and conventional foods. Organic foods can be extremely price exclusive in India and may have gaps between their claims and evidence of safety. Conventional foods are prone to environmentally unfriendly means of production and may be laden with chemical pesticides that are hazardous to both producers and consumers. Safe Harvest actively built a third category of products, "pesticide-free" foods, driven by its mission of providing safe and healthy food for all while supporting smallholder farmers.

Maintaining compliance

It keeps the promise of "pesticide-free" foods from farm to kitchen by providing end-to-end solutions to its supplier FPOs (which are also value chain partners) and having Safe Harvest staff present at facilities from harvesting through to final procurement. Its network approach enables training, grading, and ensuring FPOs and farmers can comply with standards. Safe Harvest procures multiple commodities from different FPOs across India to ensure steady supply despite environmental and other fluctuations, maintaining a diverse offering of products. It also oversees rigorous compliance across its partners and adherence to the maximum pesticide residue limits set by the Food Safety and Standards Authority of India's Jaivik Bharat (Organic India) standards. It then publicly shares the results of its product test reports to back up the "zero certification" label, reinforcing its product differentiation. Pricing the products at only 10%–20% higher than conventional products unlocks the price-sensitive but enormous middle-income consumer segment for these products (Safe Harvest interviews).

Raising finances

One of Safe Harvest's key sub-innovations was its capacity to effectively plan and raise finances. Since it was introducing a whole new category of food products, there was a longer timeline envisioned to establish the concept, build the market supply chain, bring economic returns, and see a greater benefit to the public, especially as it worked with small and marginal farmers who were often more remote. Even without the existence of a supportive financial ecosystem for such an enterprise, Safe Harvest innovated on its capacity to tap into varied sources of finance to suit its needs throughout this journey. The initial grant from the Ford Foundation helped establish the category by catalyzing the NPM Network's efforts to help farmers commit to "pesticide-free" practices. It also allowed the Network to collectivize and align on its priorities, which was key in defining financial goals, among others.

After its 2013 restructuring, Safe Harvest raised four rounds of equity and was able to attract key impact investors like Ashish Kacholia, who continues to support the company in improving its financial credibility and raising debt with his investment expertise. The increased confidence from investors led to unique tripartite agreements with credit institutions and increased Safe Harvest's and its partner FPOs' operational capacity, as the FPOs' creditworthiness also improved. One key agreement was with Friends of Women's World Banking–India and Ananya Finance as a direct lender; here, Safe Harvest took the cost of financing and FPOs transferred custody of aggregate commodities to Safe Harvest. The novelty here lay in Safe Harvest's willingness to repay loans on behalf of the FPOs. Taking on the interest liability of separate organizations, especially young FPOs without credit history, is an uncommon practice, and shows the long-term perspective of Safe Harvest. Having underwritten many such agreements, Safe Harvest has been successful in acquiring debt to support its operations and growth.

Encouraging buy-in

Some FPOs even invested in Safe Harvest in 2014 and 2015 to increase the scope of how the farmers and company work together; in 2022, FPOs held 0.5% of shares. Moving from stakeholders to shareholders also provides evidence of the FPOs' commitment to non-pesticide management and direct market linkage. Together, the innovations in funding enabled Safe Harvest to increase its volume and reach and establish the "pesticide-free" category. By actively building this context for itself, Safe Harvest has also built the context for other market players to enter and retail under the "pesticide-free" category of food.

Outcomes and impacts

Through Safe Harvest's network, FPOs have gained skills in market preparedness, value addition, aggregation, and storage. Some have climbed up the value chain, allowing them to earn a greater share of the consumer rupee: 15 FPOs now supply clean and graded agricultural commodities to Safe Harvest; one of these also packages more than a dozen products for the retail market; and five others are able to supply Safe Harvest with retail-quality products that don't require further processing or manual cleaning. These FPOs have also been able to increase their collective negotiation capacity and power with different potential buyers.

Social impacts

The social impacts begin with health. Studies evidence the ill effects of chemical pesticides on human health, and reducing exposure to these pesticides also reduces the scope of hazardous exposure (Bhardwaj and Sharma, 2013; Grewal et al., 2017; Sharma and Singhvi, 2017). Transitioning to non-pesticide management reduces hazardous exposure and improves the health of farmers, their families, and their communities. Consumers of "pesticide-free" products, too, avoid pesticide residues in their food. Safe Harvest has always advocated for compulsory residue testing and greater transparency to the consumer in general, and set the benchmark by being the first to have its testing information available publicly. The Food Safety and Standards Authority now mandates testing for pesticide residue for all agricultural commodities.

Economic impacts

In terms of economic impact, Safe Harvest has enabled access to a stable, profitable, transparent and organized market for 100,000 small, marginal, and tribal farmers across 12 states of India. Transacting directly with FPOs, it offers farmgate prices that are comparable to those of the Agricultural Produce Market Committees run by state governments. By collecting at the farm gate, Safe Harvest saves farmers the fees, commissions, and transport costs associated with the Market Committees, which can be considerable for farmers located in remote areas (Anil, 2019). Safe Harvest also reported a drastic reduction in farmers' input costs from INR 2,500 (USD 33.8) to INR 100 (USD 1.35) per hectare because of non-pesticide management practices (Safe Harvest, n.d.). The amalgamation of reduced cost of inputs and increased savings led to most farmers reporting a 20% or more increase in income (Anil, 2019). On the consumer end it has brought accessibly priced products to a greater group of consumers who are conscious of health and environmental issues but cannot afford organic food.

FPO development also has socioeconomic benefits. Due to assured market access and available working capital, FPOs can invest and upgrade their capital assets (Anil, 2019). They are able to build capacity to vertically integrate value-addition activities like aggregation, stockage, cleaning, and grading, diversifying their income and capturing more of the consumer rupee. Furthermore, FPOs are able to access finance via tripartite agreements with Safe Harvest and formal lenders, improving their creditworthiness and allowing them to deal with larger volumes. Safe Harvest also helps young FPOs with no credit history access credit from institutions like NABKISAN (a subsidiary of the National Bank for Agriculture and Rural Development) and Friends of Women's World Banking–India. With such formal financial access enabled, the government's infusion of up to INR 10 lakh (USD 13,345) more under the matching equity program has helped FPOs raise equity and proportionately higher debt. Eleven FPOs have received loan linkage facilities via Safe Harvest from non-banking financial companies like NABKISAN, Ananya, Avanti, and Friends of Women's World Banking–India on different occasions, varying from INR three lakh (USD 3,998) to INR three crore (USD 400,384).

Environmental impacts

Finally, Safe Harvest's new product category has had multiple positive environmental impacts. Non-pesticide management training to farmers has reduced the entry of hazardous compounds into the environment and food chain, mitigating well-documented ill effects of pesticides on ecosystems (Bhardwaj and Sharma, 2013; Grewal et al., 2017; Sharma and Singhvi, 2017). The management approach is also water smart: by focusing on limiting chemical fertilizers and progressively increasing organic manure and biofertilizers, *in situ* moisture is maintained and the need for irrigation is reduced. FPO partners are mindful of the depth of irrigation for crops such as monsoon-season rice, which increases the efficiency of water cycling through the system and reduces risks of water quality deterioration (Safe Harvest interviews). Soil-enhancing practices are further combined with crop rotation, mixed cropping, and intercropping to generate positive impacts on soil health. Biodiversity is enhanced as the adoption of non-pesticide management reduces the harm from chemical pesticides and fertilizers.

While an immediate transition from input-intensive farming to chemical-free farming is very risky and difficult for small and marginal farmers, the adoption of non-pesticide management has created an essential stepping stone toward it. Many farmers have upgraded to further environmentally positive practices beyond non-pesticide management over the years, including the full transition to organic and other chemical-free farming models (interviews with leadership of Nature Positive Farming, Wholesome Foods Foundation and Samuha, August 17, 2021).

Success factors

A foundation in experience

The founding members and leaders in Safe Harvest came from well-established NGOs with years of field experience in development. They were able to leverage their experience, knowledge, and networks to build solutions grounded in a nuanced understanding of immediate context and farmer needs. Just as importantly, Safe Harvest as an organization has been well aligned to its principal value of making safe and healthy food available to all by supporting small and marginal farmers. The company ensured internal alignment to this value and the need for long-term thinking and trust-building. This allowed it to persist and invest in building itself, its supply chains, and its partnerships through all the ups and downs that have led to its current growth phase. Because the vision aligns closely with that of the NPM Network from which Safe Harvest emerged, the network has offered key support in training and developing the capacity of Safe Harvest's FPOs.

Evidence and presence

The characteristics of the "pesticide-free" product category as an innovation are also key to its success. Notably, the innovation is based on a foundation of sharing evidence to build trust of the consumers in Safe Harvest's "zero certification" label. This includes making the results of product verification tests publicly available, ensuring all claims are verified and reliable. Meanwhile, procurement from multiple states across the country not only supports the year-long on-shelf presence of Safe Harvest's products, building resilience against environmental and supply variability, but also broadens its product selection. These factors significantly increase the potential touch points with any prospective consumer, giving Safe Harvest a notable market presence while keeping the organization lean. The number of commodities that Safe Harvest deals in increased from 40 in 2018–19 to 55 in 2021–22.

Farmer ownership

As Safe Harvest brings in FPOs as partners, it enables the FPOs' sense of ownership. Such partnerships have allowed the company to bridge expertise gaps and strengthen its operational capacity. As it showed its commitment to working with FPOs and supporting them through the process of training and procurements, Safe Harvest was able to build good faith, with some FPOs even displaying their ownership by becoming shareholders. This made the process of developing supply partners for a new market context easier, and attracted other FPOs to seek out Safe Harvest. The number of partners that Safe Harvest transacts with increased from 22 in 2018–19 to 30 as of August 2021. By the latter date, Safe Harvest was working with 10 more organizations that were in the process of forming farmer collectives.

Investor trust

Safe Harvest also leveraged its financial and development-world networks and built relationships with institutions and individuals where they could mutually support Safe Harvest's financial needs and the partners' goals. Here, too, building trust was key. The partners included individual investors, institutional investors, formal institutional lenders, non-banking financial companies, and even FPOs that hold shares. The diversified pool of funds, including grants, debt, and equity from different funding partners, was put to judicious use by capitalizing on different funding mechanisms from different partners. Safe Harvest's investors have focused on particularly long time horizons and bought into Safe Harvest's capacity for social impact and its vision, which kept their buy-in through challenges. India's largest impact investor, Ashish Kacholia, was a determined investor with the resources to take on a high-risk venture with a long time horizon, and he also helped Safe Harvest strategize through its restructuring. Another investor, Friends of Women's World Banking–India, was able to provide financing even when Safe Harvest was a new entity that was incurring losses, didn't have an established supply chain, and was working with "higher-risk" farmers, because of the trust and vision Safe Harvest has built and evidenced in its institutional design and collaborative capacity.

Future challenges

Building a category, getting shelf space, selling the products, and reaching profits is a long journey that requires capital insertion and sustained support. Financiers are needed at different points of an enterprises' journey to support the unique needs in each stage, including both equity and debt. As debt financing isn't easily accessible from formal financial institutions, Safe Harvest has to rely on non-banking financing companies, which can be expensive. Along with equity investors who are aligned on values and are open to investing in a longer time horizon, support from formal banks to provide working capital at early stages over a longer period would enable the organization to grow and bring results faster. On the other hand, Safe Harvest has been prioritizing financial sustainability over fast results and the company seems content to scale up at its own speed.

Finding and matching investors who can align with the vision—where farmers are the final stakeholder and are willing to take on long-term investments—is essential, and remains a challenge for such enterprises. The vision requires eventual hand-off of greater shares of ownership over the value chain to FPOs and farmers, so that in the event of an investor wanting to exit and sell, the institutional design and the vision will stay intact. Safe Harvest has been actively engaging with its FPOs to ensure their ownership of the value chain, toward the goal of a complete hand-off where Safe Harvest only remains as their marketing and branding partner. This is central for other organizations within the social innovation and development sector, as well, to ensure impact beyond their tenure while also supporting systems resilience.

Trustea

Tea is a top consumer beverage in India, and the country comes second only to China in tea production (Jaisimha, 2019). While historically tea was primarily cultivated for export purposes, currently about 80% of India's tea production is for domestic consumption. This has changed the landscape of tea cultivation; while tea estates primarily cater to the global market, the supply to the domestic market comes from smallholders (Langford, 2019). Small tea growers (STGs, defined as having up to 25 acres or 10.12 hectares of tea cultivation) now contribute about 50% of India's tea production (Consultivo, 2020). While estates process their tea on-site, smallholders transport their tea to factories—either the estate factories or bought leaf factories that source at least two-thirds of their tea from outside growers. The factories then process the tea and sell it through auction centers or directly (Langford, 2019).

Historically, STGs and bought leaf factories often lacked knowledge on sustainable practices and the resources to adopt them, and the working conditions in both were often poor (Asia Monitor Resource Centre, 2010). Because the global market sourced its tea chiefly from large estates, the Indian estates that exported tea were governed by global private standards such as Rainforest Alliance and Fairtrade, which ensured that producers met certain product and process standards (Langford, 2019). Standards only governed this small fraction of India's tea producers, however. STGs were disconnected from global standards, and concerns arose regarding the well-being of their workers, the quality of their tea, and the sustainability of their production (Langford, 2019).

History of trustea

The push for self-regulation

A confluence of actors in the global and domestic markets has facilitated the push for self-regulation among STGs in producer countries (Langford, 2019). While Unilever and Tetley (owned by Tata Consumer Products) control 16% of the global tea market (Potts et al., 2010), about 45% of India's domestic market is controlled by Hindustan Unilever Limited, a subsidiary of Unilever, and Tata (Singh et al., 2021). As early as 2007, Unilever took the lead in adopting Rainforest Alliance certification for all their tea sold in the European Union, and in 2010 they announced a vision to shift to 100% sustainable sourcing by 2020 (Unilever, 2010; interview with Mr. Daleram Gulia, Procurement Manager for Sustainability at Hindustan Unilever, August 24, 2021). To achieve this, Unilever attempted to introduce Rainforest Alliance certification across all their tea sourcing regions. This proved difficult in India, as there existed differences between Rainforest Alliance's code of conduct and Indian labor laws (Langford, 2019). For example, the minimum permitted age for a tea worker under the Rainforest Alliance code was higher than the age allowed under Indian labor laws.

In the face of differences in product and process standards between global and domestic markets, as well as other challenges from the fragmented smallholder tea industry in India and the organization's lack of outreach to STGs, Rainforest Alliance was not successful in bringing self-regulation to STGs as per its global standards (Langford, 2019). While creating an India-specific Rainforest Alliance standard that aligns with Indian labor laws could have been easier, Rainforest Alliance did not wish to create regional variation in its certification. These factors led to the recognition of the need for a domestic standard that was specific to the Indian domestic market. Based on this context, Hindustan Unilever envisaged the establishment of a multi-stakeholder program based on industry realities and globally accepted sustainability principles. Unilever's existing Sustainable Agriculture Code—a collection of Good Practices which aim to codify important aspects of sustainability in farming and apply them to supply chains—would provide the standard with a robust and credible framework (interview with Sustainability leadership at Hindustan Unilever, August 24, 2021).

Around the same time, Indian consumers were gaining awareness of the need for safer tea. A report by Greenpeace (2014) found "highly hazardous" and "moderately hazardous" pesticides in tea samples, including those collected from major brands such as Hindustan Unilever, Tata, and Wagh Bakri, outraging tea drinkers. To counter this, the Tea Board of India—a quasi-autonomous government body that authorizes, registers, and licenses industrial activities within the tea industry—came out with a Plant Protection Code for the use of pesticides on tea. However, the Tea Board of India didn't have the wherewithal to enforce the code, and Indian NGOs felt that this move was insufficient to address the spectrum of challenges faced by smallholder producers, such as deplorable working conditions (Langford, 2019).

A tea standard for India

Interests and influences driving self-regulation in the Indian tea industry were not limited to Hindustan Unilever alone. The Dutch organization IDH–The Sustainable Trade Initiative was also working for sustainability in the tea industry through their Tea Improvement Program. Upon seeing IDH's interest in funding standards for self-regulation within domestic markets, Hindustan Unilever approached IDH about the Indian tea industry (Langford, 2019). Later, IDH reached out to Tata Consumer Products, making Trustea an industry-wide initiative. Tata also brought in a collaboration with the Ethical Tea Partnership, which played an important role as one of the implementation partners in Assam, West Bengal, and Kerala (interview with Sustainability leadership at Tata, August 18 and 23, 2021).

To design a standard for tea production in India, Unilever approached Solidaridad Asia, an NGO based in New Delhi. Its parent NGO, Solidaridad, had previously played a key role in designing, developing, and mainstreaming standards within the markets of global firms for many commodities. The organization also provided training to improve producers' uptake of certifications. Solidaridad Asia collaborated with Hindustan Unilever, and together they developed the initial draft for a standard of self-regulation for Indian tea producers that accounted for the intricacies of the domestic tea market (Langford, 2019).

Building on this foundation, Hindustan Unilever, Tata, and IDH came together to launch Trustea in 2013—an Indian verification system and sustainability code for the tea sector. After the launch, these three partners plus the Ethical Tea Partnership and Solidaridad co-created the final form of the code. Sector-level multi-stakeholder engagement, decision making, and action *via* Trustea ensured that the further evolution of the Trustea code and its mainstreaming would happen in a planned and strategic manner. With early support from a state regulatory body, the Tea Board of India, Trustea further ensured that it would not face any administrative hurdles with the government.

Industry engagement

The Trustea code works toward overcoming the multiple challenges of the tea industry (Table 1). It enables producers, buyers and others involved in the Indian tea business to obtain tea produced according to "agreed, credible, transparent and measurable criteria" (Trustea, 2021). Many STGs were initially unable to adopt the practices of the sustainability code, whereas large tea estates had the resources and infrastructure to adopt the certification, but had to be aligned to the business case and understand the benefits. Trustea, therefore, engaged with factories in estates, bought leaf factories, and representatives of grower groups for compliance and certification under the code; these, in turn, worked with STGs. Trustea certified bought leaf factories, and the chain of custody established here let Trustea train STGs and build their capacity through factories. This chain of custody also aided factories in keeping track of the quality of tea (Trustea, 2021). The stakeholders who engage with Trustea continue to take note of changes happening in the market, consumer demand, and environment, in order to upgrade or modify the Trustea code accordingly.

Trustea began operation with funds provided by IDH, Hindustan Unilever, and Tata, later strengthened by the joining of Wagh Bakri Group in 2017. Hindustan Unilever and Tata have contributed equally to the Trustea code, to the tune of INR two crore (USD 265,362) every year. IDH contributed INR three crore (USD 398,044) a year until 2020, and Wagh Bakri has contributed INR 50 lakh (USD 66,350) a year since joining (interview with Sustainability leadership at Tata, October 18, 2021). Currently, Trustea is transitioning toward a new business model where it will monetize the Trustea seal on retail packs. Trustea will continue to provide free-of-cost training and capacity-building activities to all stakeholders, and the cost will only be borne by companies who put Trustea seals on their packaging. Until such a time as it reaches a break-even point, Trustea will continue to receive financial support from its funders.

Out of an estimated 250,000 STGs and 3.5 million tea workers in India (Rajbangshi and Nambiar, 2020), Trustea had by 2020 engaged with 81,841 tea growers and 640,000 workers (Figure 4). The STGs with whom Trustea has engaged are an average of 57 years old; most have completed a primary level of education; and 90% own an estate smaller than five hectares

TABLE 1 Key points under the Trustea code.

Dimensions of Trustea code	Summary of applicable control points pertaining to the dimensions
Management system and continuous improvement	Verified farms have an easy to maintain and practical management system in place for complying with the Trustea code and applicable legislative requirements
Product traceability	Verified farms and facilities develop a clear and visually identifiable system for avoiding the mixing of verified products with non-verified products in its facilities
Water management	Verified units ensure that they are using water efficiently, with minimal loss and optimal use
Fertilizers	Proper selection of kind and volume of fertilizers, but also its safe application and storage
Plant Protection Formulations (PPF)	The selection of Plant Protection Formulations (PPF), their use and storage are mandated as per the Plant Protection Code (PPC) of India
Food safety	Adherence to the Indian Food Safety and Standard Act, 2006 for greater control over the quality, safety of tea and reduced rejections from national and international buyers
Safety, health and welfare of the workforce	Verified units analyze and strive to prevent all potential adverse effects on the health or working conditions of workers and have an action plan in place to reduce and prevent the risk of accidents in the workplace
Working conditions and workers' rights	The verified units must comply with national and state legislations on relevant labor legislations that apply to the tea industry

(Trustea, 2021). Trustea has certified 695 estates and bought leaf factories, covering 56% of all tea produced in India (Trustea, 2020a).

Trustea's innovation

Establishing private self-regulation

Trustea's core innovation is its process of self-regulation (as defined in Gupta and Lad, 1983). Its code is governed and facilitated by a diverse and inclusive multi-stakeholder council with buy-ins from tea brands, tea producers (large tea estates, STGs, bought leaf factories), NGOs, civil society, research and academia (Figure 5). The council is divided into a funding committee (IDH, Tata, Hindustan Unilever and Wagh Bakri) and a program committee (IDH, Tata, Hindustan Unilever, United Planters' Association of Southern India, Indian Tea Association, Confederation of Indian Small Tea Growers' Associations, Assam Bought Leaf Tea Manufacturers' Association, Tea Research Association, Gujarat Tea Processors and Packers Limited, and UN Women). The council is collectively responsible for taking all the decisions of Trustea in a consensual and aligned manner. The decision to have representation from various categories of stakeholders in the domestic tea industry is a strategic one to ensure impact and buy-in throughout the industry.

Building small tea grower capacity

Trustea does not stop at verification, like some other certification efforts, but also invests in building the capacity of STGs, bought leaf factories, tea workers, and other producers to ensure compliance. A unique aspect of this procedure is that Trustea engages with STGs through estate factories and bought leaf factories. These factories share lists of STGs who provide them with their tea, and Trustea undertakes training of these STGs as per the requirements of the code. By establishing this chain of custody and putting the onus on these factories, Trustea has attempted to address the problem of chasing every STG to ensure their compliance and adherence to the code. This process also aids the factories and Trustea in maintaining traceability and quality of the produce.

Trustea's capacity-building processes are tailored for easy comprehension by STGs and tea workers and employ community engagement, community building, and experiential learning. Based on observations that STGs learn well through live demonstrations, Trustea devised a concept of model farms wherein tea growers learn to practice sustainable methods on farm, discuss their challenges, and seek resolution by trained personnel and fellow growers. One of the most recent efforts, Tracetea, is a digital platform and traceability application where STGs can register, conduct business, discuss their problems, suggest solutions, and interact with other STGs across the nation. Tracetea has been successfully piloted in West Bengal, Assam, and South India (Trustea, 2021).

Implementing with a local presence

For implementation, Trustea linked up with multiple entities such as the Tea Research Association, Action for Food Production, Reviving the Green Revolution (an associate of Tata Trusts), Ambuja Cement Foundation, and the National Skills Foundation of India. These implementation partners were selected after evaluation of their alignment with Trustea and their local presence, and they play an instrumental role in providing training and hand-holding support to stakeholders. The implementation partners employ local personnel and execute capacity-building activities so that there are few trust, language, or community/region-specific barriers. Audits on the stakeholders are conducted via third-party vendors.

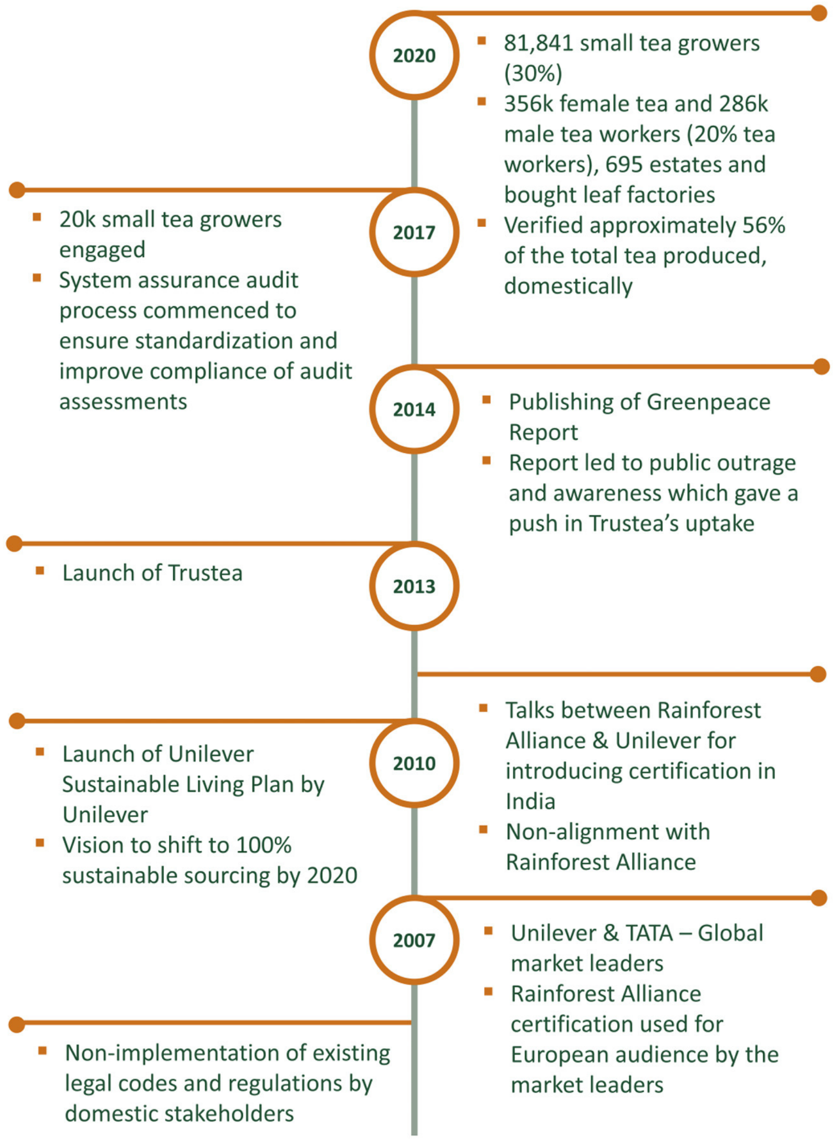


FIGURE 4
Timeline of key events in Trustea.

Outcomes and impacts

Environmental impacts

As an initiative rooted in sustainability goals, the Trustea code has had multiple positive environmental impacts. Tea being a water-intensive crop, Trustea encourages the adoption of practices that improve water use efficiency and sewage management by mandating these in the code. They have introduced extensive training and guidance on water management practices for verified units, but have not been able to verify compliance, especially by STGs (interview with leadership at Trustea, October 11, 2021). More than 50% of STGs associated with Trustea have, at least, introduced control mechanisms for chemical runoff and sewage (Consultivo, 2020). To enhance the soil quality of tea estates, Trustea also mandates adherence to the Plant Protection Code and the use of Food Safety and Standards Authority-approved chemicals within allowed limits. Through the training and capacity building of STGs, adherence to the Plant Protection Code has seen noticeable improvement (Langford, 2019). Additionally, more than 80% of certified STGs were recorded to have adequate storage and segregation facilities in their tea gardens (Consultivo, 2020).

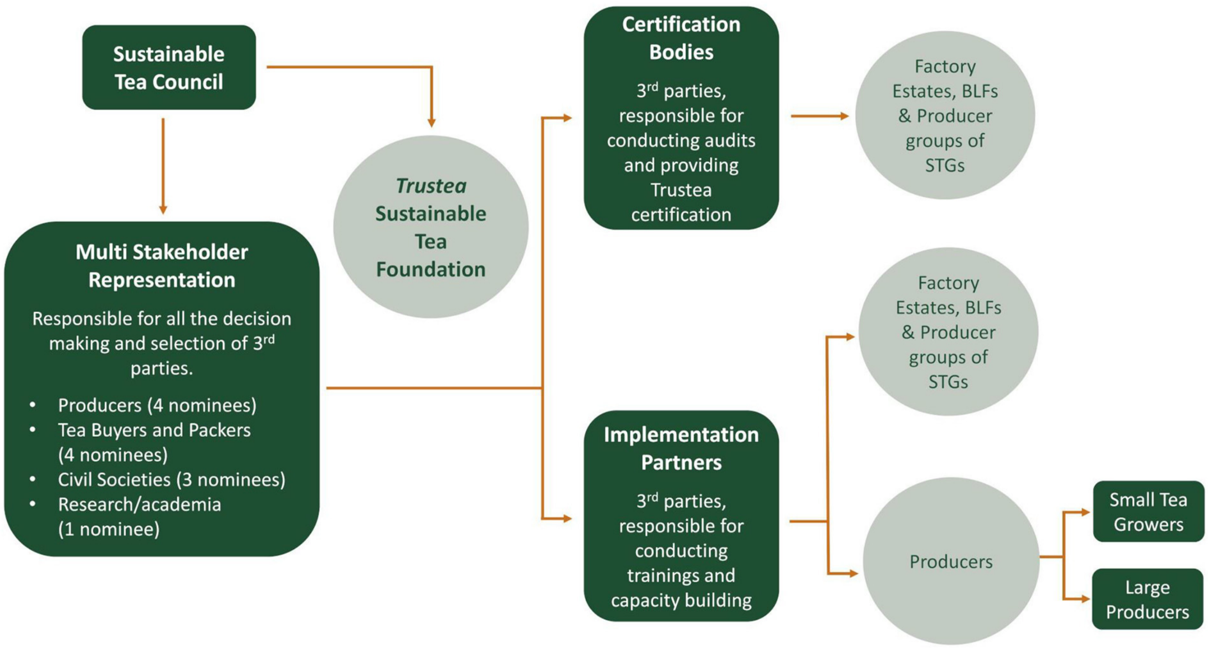


FIGURE 5
Representation of Trustea stakeholders, including bought leaf factories (BLFs) small tea growers (STGs). Authors' creation based on Trustea (2020b).

Food safety impacts

All verified STGs and bought leaf factories have been introduced to food safety guidelines of the Tea Board of India and the Food Safety and Standards Authority of India on good hygiene and manufacturing practices through systematic training and assessment programs. The training and knowledge have led to increased awareness of the guidelines and facilitated their compliance, resulting in higher production of safe tea (Trustea, 2021).

Social impacts

From the beginning, Trustea has focused on achieving compliance with national and sector-specific labor laws among its target entities and STGs. The zero-tolerance approach and training on eliminating child labor (under 14 years of age, as per Indian law) and wage disparity have led to decreases in both at Trustea-verified entities (Trustea interviews). Workers are given extensive training on the handling of fertilizers using safety equipment, and the Trustea code only allows fertilizers and plant protection formulations that are non-hazardous and approved by the Plant Protection Code. These practices have reportedly resulted in reduced worker exposure to chemicals and improvement in their health conditions [Trustea interviews and (Consultivo, 2020)]. In 2020, Trustea further ramped up hygiene and sanitation requirements for certified entities in light of COVID-19, which led to the establishment of sanitizer provisioning facilities in tea estates.

Success factors

Enabling environment

The circumstances and enabling environment in which Trustea emerged have without a doubt been key to its success. The Greenpeace (2014) report was instrumental in raising awareness among Indian tea consumers and other stakeholders about sustainability challenges in the sector. Even after the Tea Board of India launched its Plant Protection Code, the clear gaps in the regulation of the domestic tea industry necessitated a self-regulation mechanism. The Tea Board of India therefore supported Trustea from the start, chairing Trustea meetings, sending out invitations, and gathering rapid approval from the entire industry. This then led to easy collaboration with other regulatory bodies like the Food Safety and Standards Authority, enabling the development and standardization of safety standards for tea.

Industry commitment and credibility

While regulatory endorsement created a push for the adoption of Trustea standards, a corresponding pull came from the strong commitment of market leaders like Hindustan Unilever, Tata, and Wagh Bakri, who controlled more than half of the tea market and made clear their preference for purchasing only sustainably produced tea. Trustea worked with research institutions like the Tea Research Association, as well, to ensure that its practices were backed and validated by the scientific community. Their involvement gives credibility to the code's manual and guidelines, and authentication to its requirements and benefits, leading to greater acceptability of the code in the tea industry.

A diverse governing council

The diversity of the Trustea council ensured that Trustea had access to domestic and international expertise, market knowledge, and networks to enable informed strategy and decisions. Its association with the international organization IDH, which had expertise in driving sustainability in supply chains of food commodities, tremendously aided in the development and drafting of the code (Langford, 2019). The support of domestic implementing partners like the Ethical Tea Partnership (associated with Trustea until 2019) and Solidaridad Asia (associated until 2018) provided an in-depth understanding of domestic tea production and supply chains. Their technical expertise ensured the successful development of the field implementation chain for the code, which resulted in higher compliance rates.

A shared understanding

The multi-stakeholder council has been able to function effectively around a shared understanding of the need for sustainability standards. Trustea holds multiple pre-engagements talks with prospective council members before inviting them in to cement their shared understanding. The council's consensus-based decision making and voting procedures aid in developing trust, and it is strictly enforced that all activities of Trustea are in a pre-competitive space; the only objective of collaboration among stakeholders is for achieving the common goals of the Trustea program. The shared outlook of the council members has also transformed into shared investment. Hindustan Unilever and IDH brought in the first funds, and their commitment reinforced the credibility of Trustea, motivating other stakeholders to step in. The funds contributed each year by funding partners are allocated against the activities that are planned for that particular year; this clarity, flexibility, and transparency works as a catalyst for establishing trust among the funding partners.

Interactive learning

As a business model, Trustea believes that a high compliance rate can be achieved among financially and educationally weaker audiences through interactive learning. Research shows that these audiences comprehend information better via live demonstration (Consultivo, 2020), which inspired Trustea's model farms and the creation of animated videos for STGs. The training manuals and education modules under the code are also creative and interactive and are made available to growers in their regional languages. In addition, Trustea-provided market intelligence on auction centers, purchasers, and new varieties of tea has ensured the interest and participation of STGs, bought leaf factories, and factories in estates.

An evolving code

Although Trustea is clear in its vision and goals, the diversity and magnitude of the Indian tea sector means that the model also has to be flexible and responsive to feedback from stakeholders. The initial version of the code launched in 2013 received a great deal of this feedback that was later re-worked into the current code, resulting in high acceptability and compliance. Further, in order to enhance the credibility of the Trustea code and accredit it with the globally accepted sustainability principles, Trustea has become a community member of the ISEAL Alliance, a global organization working toward tackling sustainability issues through a collaborative approach.

Future challenges

Tea is sensitive to the environment in which it is grown, and any change in conditions can affect production in terms of quality and quantity. Climate change is already being witnessed in tea-producing areas of India in the form of erratic rainfall, new pest infestations, and changes in temperature (Nowogrodzki, 2019). However, the Trustea code is yet to introduce guidelines on adapting to climate change for its verified units.

Another challenge is traceability. Trustea engages with STGs through estate factories and bought leaf factories, and both are stringent in ensuring that STGs provide them with tea produced to the Trustea standard. Though this chain of custody helps the factories maintain traceability and quality of tea, certain aspects bring down the efficiency of the process. The tea produced by bought leaf factories and factories, apart from being sold directly to big private players, is also sold through auction centers. The buyers at these auction centers may or may not care about the sustainability and quality of tea. When tea is sold to such buyers, there arises a possibility that factories will not be sufficiently compliant with the certification code. Though Trustea has introduced the Tracetea traceability application to overcome this problem, the application is still in its pilot phase and has a long way to go.

Public procurement is also an open question. Government institutions such as Indian Railways and the military Canteen Stores Department are major bulk buyers of tea, and Trustea is yet to tap into this market. This is a long procedure to traverse in the absence of factors like a sustainability-focused policy framework, advocacy, lobbying, and consumer demand. Though Trustea has had the support of the Tea Board of India, given the lack of coordination among different government ministries and departments, that initial support will not help Trustea in this respect.

Lastly, sustainability as a concept in tea is still nascent in India. Though Indian consumers are slowly beginning to recognize the importance of consuming safe and sustainably produced tea, there is a lack of knowledge and interest in recognizing and rewarding tea brands working on these parameters. Brands that have faced similar challenges in different industries in the past have spent copious time and money to overcome them. For example, in order to get Indian consumers accustomed to sanitizing their hands, the Savlon brand launched a massive campaign in India with the hashtag #NoHandUnwashed (exchange4media, 2020). Given this precedent, it will be interesting to witness how Trustea as a sustainable tea brand can overcome the existing gaps in consumers' minds and create a space for its Trustea seal in the Indian tea market.

Discussion

Safe Harvest was founded as an answer to farmers' demands for market access and product differentiation. As a case study, it demonstrates the capacity for impact when small and marginal farmers and their needs are centered in the innovation process. Safe Harvest created a new market category of "pesticide-free" products and supported FPOs to become supply chain partners, which was crucial for smallholder farmers who lack access to consistent market linkages and pricing mechanisms and who have no viable path to organic farming. Non-pesticide management and Safe Harvest's back-end design ensured accessibility for farmers in line with the vision for impact. Safe Harvest has been able to do this by keeping value-driven leadership at the helm and creating trust, long-term engagement, and collaborative capacities as part of its institutional design. Transparency and inclusiveness were key characteristics of its successful partnerships with FPOs, as opposed to top-down dynamics and transactionality. These choices also created operational sustainability by positioning farmers as primary stakeholders with a sense of ownership, demonstrated in the independence of partner FPOs, which are now engaging with other market players.

Safe Harvest has required continuous support from financiers who share its vision, align on the innovation model, understand the need for long time horizons, and are willing and able to creatively support a growing organization's changing needs. It has been able to find this by tapping into a network of diverse financiers in grants, debt, and equity, and the case displays the need for an aligned investor ecosystem for any ventures taking on similar challenges. Empowering localized economies and contextualized financing mechanisms can build pathways for ventures like Safe Harvest to flourish and grow, opening up possibilities of well-supported, value-driven, grassroots-centered social enterprises if supported by the right investment ecosystem.

The case of Trustea, meanwhile, carries important lessons on how self-regulated certification alongside strategically planned bundles of interventions can create impact on an entire value chain. Trustea has emerged as a significant player who successfully set up a sustainability standard for the Indian tea industry. Through its targeted focus on establishing a multi-stakeholder council and capitalizing on the skillsets of its members, Trustea ensured support from every key player in the industry. One of the most notable outcomes of the council was its ability to maximize the market hold and strength of players like Hindustan Unilever Limited and Tata Consumer Products and pull tea producers toward sustainability. The success of this multi-stakeholder initiative highlights the significance of alignment, clear goals, and well-defined operational procedures among such collaborators.

The initial support offered by the Tea Board of India played an instrumental role in Trustea gaining acceptability in the tea industry, underlining the ease which comes with the backing of a state regulatory body. The focus of Trustea on creating tailored capacity-building activities led to high compliance with its code, and working with varied value chain actors created interdependency among these actors, enabled the smooth operation of value chains, and developed accountability. Inclusivity in collaborations worked as another important factor for Trustea's scaling and outreach to a diverse audience. Continuous internal and external audits have aided Trustea in keeping track of compliance rates and addressing gaps. While it has achieved notable scale, it remains to be seen how the program can adapt and maintain its growth, build its brand image among Indian consumers, and deal with changes in climatic conditions.

Conclusions

A number of conclusions from these case studies provide learnings—not only for India, but also for other countries in the Global South seeking to enable innovation pathways toward sustainable agri-food systems.

Firstly, end users need to be placed at the center of innovation through sustained engagement and tailored, context-specific solutions. Even top-down programs (as both of our cases ultimately are) can maintain such bottom-up characteristics through a constant push by the leadership: building bottom-up communication channels, training and sensitizing staff, and instituting a project design that enables sustained community engagement. Safe Harvest and Trustea ensured that they weren't *only* top-down efforts; they actively worked with farmers and ensured information flowed both ways. The creation of Safe Harvest itself was driven by the need expressed by end users, and the needs of smallholder and tribal farmers were centered throughout the creation of FPOs, supporting access to finance, and the focus on pesticide-free as opposed to organic production. In both of our cases, we note that engaging and understanding end users and their context not only led to high uptake but also built trust and credibility among end users.

Trust is a transcendental element that is central to the sustainability of all stakeholder relationships, and thus of the innovation itself. It goes beyond trust with end users to trust between partners and the trust of funders. It's also inextricable from the values with which these private actors approach each relationship—and particularly relationships with farmers, where any extractive impulses must be countered. Alignment in long-term vision is key; Trustea, in its case, was able to work through a dynamic and diverse council because of its strong focus on establishing alignment within the stakeholders through multiple pre-engagement talks before formally collaborating with them. Trust is also established through evidence generation. Safe Harvest generates relevant evidence for its end users (both farmers and consumers) through its "zero certification" mark and the publicly available data from the verification tests behind it, while Trustea has been able to increase the acceptability of its code among stakeholders by engaging research and academic institutions to validate the code.

Our third conclusion is that leveraging formal and informal networks and organizations in the producer ecosystem can be an efficient and effective way to engage with a broader base. This was particularly observed with Safe Harvest, where existing FPOs were a route to scaling the farmer base of the program; outreach to smallholder farmers succeeded by leveraging the existing formal and informal social networks in the community, with a multiplier effect in scaling farmer engagement. In the case of Trustea, a private company invested in the preliminary development of a sector-wide standard and reached out informally to other players to set up a multi-stakeholder initiative that later became a formalized certification system. This reinforces the need to create room for informal interactions and actions where experimental ideas can be validated.

The fourth conclusion from these private-sector-led innovations is that government support may not be essential—but its endorsement certainly helps. This is in fact a key aspect of the enabling environment for even fully industry-based initiatives like self-regulated standards. In the case of Trustea, endorsement given by the Tea Board of India was invaluable in building credibility and trust in Trustea's vision with numerous stakeholders.

Fifth, a strategically crafted but continuously evolving bundle of interventions is essential for long-term success and scale. Bundling means implementing interventions in different areas simultaneously, such as market creation, business, policy, technology, or value chain development. Some of these areas may be within the zone of influence of the initiator, as with Trustea, where the development and promotion of the domestic standards was bundled with extensive capacity building of tea producers and awareness generation on sustainability. Other areas of intervention are outside the zone of influence of the initiator, and partnerships can enable the required bundling. For example, almost all of Safe Harvest's partner civil society organizations had highly trained agricultural professionals who enabled the development of rigorous internal systems to help farmers strictly adhere to non-pesticide management as envisioned by Safe Harvest.

Finally, partnerships drive success when they are crafted based on the needs of the innovation program, are managed rigorously, and evolve with the changing context. Staff and partners also must have a shared vision and be aligned on innovation goals. The Safe Harvest case shows that alignment to a long-term vision—including with financiers and suppliers—imparted resilience through tough times. Trustea conducted cautious pre-engagements before accepting new members into its council to ensure that all members, who might have competing interests, were well aligned with a long-term vision of sustainability in the Indian tea sector. Furthermore, the council's clear processes for decision making aided in developing transparency, trust, and communication.

It is no coincidence that partnership is so central to both of these cases. Given the many public, private, non-profit, and research entities now operating in India's agricultural landscape, partnerships seem certain to play a part in any innovation efforts—or, more likely, innovation networks—that will reach scale in the years ahead. The financial landscape will need to keep pace. Repurposed investments can power this innovation, but will also play a role in determining its direction; therefore, investors as much as all other partners have to be aligned on a vision of transitioning to more sustainable agri-food systems for India.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

AK led the execution of the entire project, provided inputs at every stage, and reviewed and edited the manuscript. NA contributed to the finalization of the research methodology, provided inputs for all case studies, and co-authored the discussion section. BJ led and authored the case study on Safe Harvest, provided inputs for all case studies, led the

organization of the report structure, reviewed, proofread and edited the manuscript, and coordinated communication logistics. DG and ATJ co-led and co-authored the case study on Trustea. ATJ provided inputs on all case studies. PFC contributed to the writing of the manuscript and coordinated the publication process. All authors contributed to the article and approved the submitted version.

Funding

The research communicated as part of this paper was funded by the International Water Management Institute (IWMI) on behalf of the International Commission on Sustainable Agriculture Intensification (CoSAI). The grant that CEEW received from IWMI was a total of USD 73,250.

Acknowledgments

Based on a research project conducted on behalf of the Commission on Sustainable Agriculture Intensification (CoSAI) (Khandelwal et al., 2022). The authors from CEEW gratefully acknowledge the contributions of stakeholders and external reviewers who were central for case study and analysis development, and research validation. The authors appreciate the support and inputs provided by the CoSAI Secretariat as well as associated commissioners toward the drafts, analysis, and approach for the study. Finally, the authors thank Richard Kohl for his extensive support through the process of drafting and analysis.

Conflict of interest

Authors AK, NA, BJ, DG, and ATJ were employed by Council on Energy, Environment and Water. Author PFC was employed by Scriptoria Ltd.

Publisher's note

References

Anil, R. K. (2019). "Linking farmer producers and urban consumers for pesticide free and safe food: Safe Harvest Private Limited," in *Farming Futures: Emerging Social Enterprises in India*, eds A. Kanitkar, and C. S. Prasad (New Delhi: AuthorsUpFront), 340–375.

Asia Monitor Resource Centre (2010). Struggle of Tea Plantation Workers in North East India. *Asian Labour Update*. Available online at: https://amrc.org.hk/content/struggle-tea-plantation-workers-north-east-india (accessed August 12, 2022).

Bhardwaj, T., and Sharma, J. P. (2013). Impact of pesticides application in agricultural industry: an Indian scenario. *Int. J. Agric. Food Sci. Technol.* 4, 817–822.

Chiodi Bachion, L., Barcellos Antoniazzi, L., Rocha Junior, A., Chamma, A., Barretto, A., Safanelli, J. L., et al. (2022). *Investigating Pathways for Agricultural Innovation at Scale: Case Studies from Brazil*. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://wle.cgiar.org/cosai/sites/default/files/CoSAI_IPS_Brazil_final_0.pdf (accessed August 12, 2022).

Consultivo. (2020). *Trustea Impact Report*. Kolkata: Consultivo. Available online at: https://trustea.org/trustea-impact-report/ (accessed August 12, 2022).

exchange4media (2020). Ogilvy India and ITC Savlon take up Mission #NoHandUnwashed. *exchange4media*. Available online at: https://www.exchange4media.com/advertising-news/ogilvy-india-itc-savlon-take-up-mission-nohandunwashed-108417.html (accessed October 25, 2021).

Greenpeace (2014). *Trouble Brewing: Pesticide Residues in Tea Samples from India*. Bengaluru: Greenpeace India. Available online at: http://www.greenpeace.org/india/Global/india/image/2014/cocktail/download/TroubleBrewing.pdf (accessed August 12, 2022).

Grewal, A. S., Singla, A., Kamboj, P., and Dua, J. S. (2017). Pesticide residues in food grains, vegetables and fruits: a hazard to human health. *J. Med. Chem. Toxicol.* 2, 40–46. doi: 10.15436/2575-808X.17.1355

Gupta, A. K., and Lad, L. J. (1983). Industry self-regulation: an economic, organizational, and political analysis. *AMR* 8, 416–425. doi: 10.2307/257830

Gupta, N., Pradhan, S., Jain, A., and Patel, N. (2021). *Sustainable Agriculture in India 2021: What We Know and How to Scale Up*. New Delhi: Council on Energy, Environment and Water. Available online at: https://www.ceew.in/sites/default/files/CEEW-Sustainable-Agricultre-in-India-2021-May21.pdf (accessed August 12, 2022).

Jaisimha, L. (2019). 11 tea producing countries that won the world tea production game. *Teafloor Blog*. Available online at: https://teafloor.com/blog/11-tea-producing-countries/ (accessed October 18, 2021).

Khandelwal, A., Agarwal, N., Jain, B., Gupta, D., and John, A. T. (2022). *Investigating Pathways for Agricultural Innovation at Scale: Case Studies from India*. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://wle.cgiar.org/cosai/sites/default/files/CoSAI_IPS_India_final_0.pdf (accessed August 12, 2022).

Langford, N. J. (2019). The governance of social standards in emerging markets: an exploration of actors and interests shaping Trustea as a Southern multi-stakeholder initiative. *Geoforum* 104, 81–91. doi: 10.1016/j.geoforum.2019.06.009

Mati, B. M., Sijali, I. V., and Ngeera, K. A. (2022). *Investigating Pathways for Agricultural Innovation at Scale: Case Studies from Kenya*. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://wle.cgiar.org/cosai/sites/default/files/CoSAI_IPS_Kenya_final_0.pdf (accessed August 12, 2022).

Moschitz, H., Roep, D., Brunori, G., and Tisenkopfs, T. (2015). Learning and innovation networks for sustainable agriculture: processes of co-evolution, joint reflection and facilitation. *J. Agric. Educ. Ext.* 21, 1–11. doi: 10.1080/1389224X.2014.991111

NABARD (2020). *Farmer Producers' Organizations (FPOs): Status, Issues and Suggested Policy Reforms*. Mumbai, India: National Bank for Agriculture and Rural Development. Available online at: https://www.nabard.org/auth/writereaddata/CareerNotices/2708183505Paper%20on%20FPOs%20-%20Status%20&%20%20Issues.pdf (accessed August 12, 2022).

Nowogrodzki, A. (2019). How climate change might affect tea. *Nature* 566, S10–S11. doi: 10.1038/d41586-019-00399-0

Potts, J., van der Meer, J., and Daitchman, J. (2010). *The State of Sustainability Initiatives Review 2010: Sustainability and Transparency*. Winnipeg: International

Institute for Sustainable Development. Available online at: https://www.deslibris.ca/ID/225909 (accessed August 12, 2022).

Rajbangshi, P. R., and Nambiar, D. (2020). Think, before you have your cup of tea! *India Water Portal*. Available online at: https://www.indiawaterportal.org/articles/think-you-have-your-cup-tea (accessed September 25, 2021).

Safe Harvest (n.d.). *The 'nature positive' revolution*. Available online at: https://safeharvest.co.in/mission (accessed September 21, 2021).

Saravanan, R., and Suchiradipta, B. (2017). *Agricultural Innovation Systems: Fostering Convergence for Extension. MANAGE Bulletin 2*. Hyderabad: National Institute of Agricultural Extension Management.

Sharma, N., and Singhvi, R. (2017). Effects of chemical fertilizers and pesticides on human health and environment: a review. *Int. J. Agric. Environ. Biotechnol*. 10, 675–675. doi: 10.5958/2230-732X.2017.00083.3

Shetty, P. K., Manorama, K., Murugan, M., and Hiremath, M. B. (2014). Innovations that shaped Indian agriculture—then and now. *Indian J. Sci. Technol.* 7, 1176–1182. doi: 10.17485/ijst/2014/v7i8.3

Singh, N., Zachariah, R., and Manna, S. (2021). Tea biggies pack a punch during Covid. *The Times of India*. Available online at: https://timesofindia.indiatimes.com/business/india-business/tea-biggies-pack-a-punch-during-covid/articleshow/86820222.cms (accessed October 26, 2021).

Singh, P. (2004). Indian agricultural development in changing scenario—past, present and future. *J. Indian Soc. Agric. Stat.* 58, 37–49.

Trustea (2020a). *Year Book 2020*. Kolkata: Trustea. Available online at: https://trustea.org/wp-content/uploads/2021/04/trustea-Yearbook-2020-1.pdf (accessed August 12, 2022).

Trustea (2020b). *Trustea Impact Report*. Kolkata: Trustea. Available online at: https://trustea.org/wp-content/uploads/2020/10/trustea-Impact-Report.pdf (accessed August 12, 2022).

Trustea (2021). *About Trustea Sustainable Tea Foundation*. Trustea. Available online at: https://trustea.org/about-trustea/ (accessed September 25, 2021).

Unilever (2010). *Unilever Sustainable Living Plan*. Rotterdam: Unilever N.V. Available online at: https://www.unilever.com/Images/unilever-sustainable-living-plan_tcm244-409855_en.pdf (accessed August 12, 2022).

World Bank (2012). *Agricultural Innovation Systems*. Washington, DC: The World Bank.

frontiers | Frontiers in Sustainable Food Systems

TYPE Mini Review
PUBLISHED 15 December 2022
DOI 10.3389/fsufs.2022.1013156

Check for updates

OPEN ACCESS

EDITED BY
P. V. Vara Prasad,
Kansas State University, United States

REVIEWED BY
Shalander Kumar,
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India
Ximena Rueda,
University of Los Andes, Colombia

*CORRESPONDENCE
Brigid Aileen Letty
bletty@inr.org.za

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 06 August 2022
ACCEPTED 16 November 2022
PUBLISHED 15 December 2022

CITATION
Letty BA, Hart TGB, Murugan S, Naidoo T, Rai S, Thiam D, Zake J, Sershen and Annor-Frempong I (2022) A critical comparative review of evidence on alternative instruments for supporting research and innovation in agri-food systems in the Global South. *Front. Sustain. Food Syst.* 6:1013156. doi: 10.3389/fsufs.2022.1013156

A critical comparative review of evidence on alternative instruments for supporting research and innovation in agri-food systems in the Global South

Brigid Aileen Letty[1]*, Tim G. B. Hart[2,3], Simone Murugan[1], Theolin Naidoo[1], Sharad Rai[4], Djibril Thiam[5], Joshua Zake[6], Sershen[1] and Irene Annor-Frempong[7]

[1]Institute of Natural Resources, Pietermaritzburg, South Africa, [2]Human Sciences Research Council, Pretoria, South Africa, [3]Department of Sociology and Social Anthropology, Stellenbosch University, Stellenbosch, South Africa, [4]Innovations Development Partners, Kathmandu, Nepal, [5]Agribio Services, Thiés, Senegal, [6]Consultant, Kampala, Uganda, [7]Forum for Agricultural Research in Africa (FARA), Accra, Ghana

Financial support is a critical enabling factor for healthy agri-food innovation systems, particularly within resource-limited settings, though additional forms of support are also necessary. This motivated a critical comparative review of evidence in peer-reviewed and gray literature on the range of instruments that support innovation in agri-food systems in the Global South, toward achieving sustainable agriculture intensification. The main aim is to provide recommendations to innovation managers on the choice of different instruments for supporting innovation. The key guiding questions for the comparative analysis were whether the instrument fosters uptake of innovation and whether it promotes inclusive development. A review of the literature was supplemented with a scan of websites for sources of peer-reviewed and gray literature documenting the application of the 12 selected instruments. The study revealed three categories of instruments: (Type A) those that support entrepreneurship; (Type B) those that primarily finance innovation; and (Type C) those that support innovation in real-life contexts. Our analysis indicates that innovation managers and funders need to select instruments that are likely to fit the specific context as well as to address the mandates of their organizations, and in so doing, they must consider how to ensure the sustainability of their investments and meet the needs of their beneficiaries. This review represents one of a handful that have compared the use of multiple instruments across multiple continents in the Global South, and can serve as an important decision-making tool for investors and funders looking to invest in agri-food innovation systems.

KEYWORDS

agriculture, innovation systems, inclusive development, decision support, evidence

Introduction

The human population in the Global South is expected to increase by 2.4 billion by 2050, coupled with a 60% increase in food demand (Fróna et al., 2019). Since smallholder farms (i.e., <5 ha in size) account for 53% of food calories produced globally (Samberg et al., 2016), it is critical that research and innovation processes lead to the development and uptake of new technical and non-technical solutions that are appropriate for these smallholder farmers. However, financial and other forms of support are critical enabling factors for creating healthy agri-food innovation systems, particularly within limited resource settings characteristic of the Global South. The need to further understand the relevance of different instruments, and related factors for their success, motivated this critical comparative review of peer-reviewed and gray literature on the range of instruments that have been used to support innovation in Global South agri-food systems, where an innovation is a new or improved solution to a need or problem (Cooke et al., 2021).

The traditional linear technology transfer model has limitations in terms of its effectiveness in promoting the uptake of technologies and innovations. Linear approaches fail to account for complexity within the agri-food system, do not deliver on outcomes, or result in unsustainable project interventions (Hellin, 2012). Furthermore, they often exclude users from the innovation process and do not address their priorities adequately (Glover et al., 2019). There is, therefore, a need for a more user-centered approach in the form of alternative instruments that support innovation processes based on user needs, resources and priorities. The potential for adopting instruments that include co-development processes involving different development partners is also important in addressing the problem (Kaimowitz, 1990; Kavoi et al., 2014). These processes require the participation of stakeholders to ensure ownership and learning from experience, and should draw on multiple sources of knowledge so that interventions are designed appropriately for a particular context (Butler et al., 2017; Brookfield Institute, 2018; Devaux et al., 2018).

The aim of this study is to provide recommendations to innovation managers about alternative instruments and their effectiveness in ensuring the uptake of innovations, as well as in supporting inclusive development where structural factors such as gender, race, ethnicity and other social categories do not exclude certain groups (van Gent, 2017). We used two key guiding questions for the comparative analysis (relative to the traditional linear transfer model):

- Does the instrument foster the uptake of innovations?
- Does the instrument promote inclusive development?

Methodology

Starting with an extensive list of documented mechanisms that have been used to support innovation in the broad field of agriculture, we eliminated those we perceived to be tools or approaches—*tools* being means to fulfill a task, and *approaches* being paradigms that inform the way that development or research is done (de Koning et al., 2021)—leaving a list of 12 instruments. We developed a data collection framework prior to reviewing literature and gathering information. In gathering data we used a mixed-methods approach that included quantitative and qualitative strategies.

The examination of peer-reviewed material, which focused on agricultural innovation rather than on research and development (to identify innovative approaches), relied largely on searches of various databases of prominent scientific journals for the period 2010 to 2020 using the search engine EBSCOhost and the following search string:

> *agricultur* AND innovat* AND challenge fund OR farmer innovation fund OR innovationgrant OR prize OR award OR insurance OR innovation platform OR innovation hub OR farmer research network OR living lab OR farmer field school OR incubator OR accelerator OR results-based contract OR broker OR intermediar**

This search was supplemented with searches on SAePublications, Sage, JSTOR and Academia.edu and the original search string was also modified to include the term *research*. The team also made use of forward and backward linkages from literature to expand the body of articles reviewed. It should be highlighted that the selection of sources/information for review was purposive in terms of focusing on the list of pre-selected instruments and thus also included literature as far back as 2003 for some older instruments.

The EBSCOhost search returned 2,105 items, of which 721 were found to relate to innovation support and involved the use of the instruments identified during the inception phase. Additional online articles, gray literature (such as project reports), and peer-reviewed articles were also screened. A total of 115 items comprising peer-reviewed and gray literature were finally included in the review and the project database.

The nature of instruments that support innovation

The review of literature showed that the instruments are very diverse and some had been used across different sectors outside of agriculture, such as water and sanitation services (Trémolet, 2015; McNicholl et al., 2020). To facilitate a comparative evaluation of the 12 identified instruments and assist with decision-making by potential users, those with similar characteristics and functions were grouped into three types. Type A are instruments that support entrepreneurship; Type B are instruments that primarily finance innovation (this excluded conventional financing instruments such as loans); and Type C are instruments that support innovation in real-life contexts (where users are operating). There are differences within and across instrument types in terms of the extent to which they support inclusive innovation and outscaling of innovations. There are also differences among the types of instruments in terms of where in the agricultural sector and along the innovation continuum they are most relevant, as shown in Figure 1. The innovation continuum is based on the definitions of Organisation for Economic Cooperation Development/Statistical Office of the European Communities (OECD/Eurostat) (2005). Brief descriptions of the 12 instruments, as well as some examples of where they have been used, are provided below to support the discussion.

Instruments that support entrepreneurship (type A)

Incubators create, nurture and develop new enterprises, thereby improving their chances of success (OECD European Commission, 2019). They can also bring new technologies, products and business models to the market by linking universities, research, enterprises and the market (Hjortsø et al., 2017). Two such programs in Africa include BioInnovate Africa and UniBRAIN (Universities, Business and Research in Agricultural Innovation), while the Villgro Incubator is an example from India (InfoDev, 2011). Accelerators, such as the Grow Impact Accelerator in Singapore, are instruments that provide short-duration support to early-stage ventures to speed up their growth (Cohen S. et al., 2019). Innovation hubs, such as the Campos dos Goytacazes Innovation Hub in Brazil (UNESCO, 2019), are generally recognized as physical co-working spaces for entrepreneurs working with technology at an early stage of development (Jiménez and Zheng, 2021), although most aim to create sustainable enterprises (Beesabathuni et al., 2021).

Instruments that primarily finance innovation (type B)

A challenge fund is a mechanism by which a funder can work with non-profit and business organizations to deliver solutions for difficult social problems (Tjornbo and Westley, 2012). The funder defines the challenge, while the private sector conceptualizes and designs the solution, provides co-finance, and implements the solution (UNDP, 2016). One such fund was Innovation Against Poverty (IAP), a pilot challenge fund launched by the Swedish International Development Cooperation Agency (Sida) in 2011 (Andersson et al., 2014). There are also different forms of innovation funds and grants, including competitive research grants and matching grants. One example is the Groupe Speciale Mobile Association (GSMA) Innovation Fund for Digitization of Agricultural Value Chains. These are increasingly used to stimulate the private sector and farmer engagement in activities related to technology generation, technology dissemination and overall innovation processes. Next, there are several forms of innovation funds for smallholder farmers (IFSFs). These instruments give farmers direct access to resources so that formal research and extension actors do not have complete control over the research agenda (Friis-Hansen and Egelyng, 2007; Triomphe et al., 2012). Some initiatives use prizes and awards to incentivize participants to solve societal challenges that may lead to major breakthroughs (Tambo, 2018). The AgResults Program, supported by various multilateral and bilateral donors and foundations, uses pay-for-results prizes to incentivize the private sector to invest in agricultural innovations. Another instrument that offers opportunities for supporting innovation is the results-based contract, which is sometimes called a pay-for-success project. However, the risky nature of agricultural research raises concerns as contractors may not be willing to take the risk unless the risk is priced into the contract (Deloitt, 2015).

Instruments that support innovation in real-life contexts (type C)

An innovation platform is a network of different actors that set themselves up to collaboratively achieve a joint objective, which may be related to a particular commodity (Boogard et al., 2013; Homann-Kee Tui et al., 2013). Several organizations and programs have promoted innovation platforms, including the Forum for Agricultural Research in Africa (FARA) and the Platform for African–European Partnership in Agricultural Research for Development (PAEPARD) (Fatunbi et al., 2016). Living labs can be described as facilities or spaces (e.g., a selected village or group of households) that are user- or citizen-centered and allow for user co-creation. The users are involved in this process from an early stage, which allows for a socio-economic assessment of the innovations (Robles et al., 2015; Cunningham and Cunningham, 2016). An example from Kenya is the Nakura Living Lab, established through the REFOOTURE project (Food Futures Eastern Africa), which will also establish living labs in Ethiopia and Uganda (WUR, 2021). Several different farmer research structures exist, including farmer research networks (FRNs), as used by the McKnight Foundation (Navarette et al.,

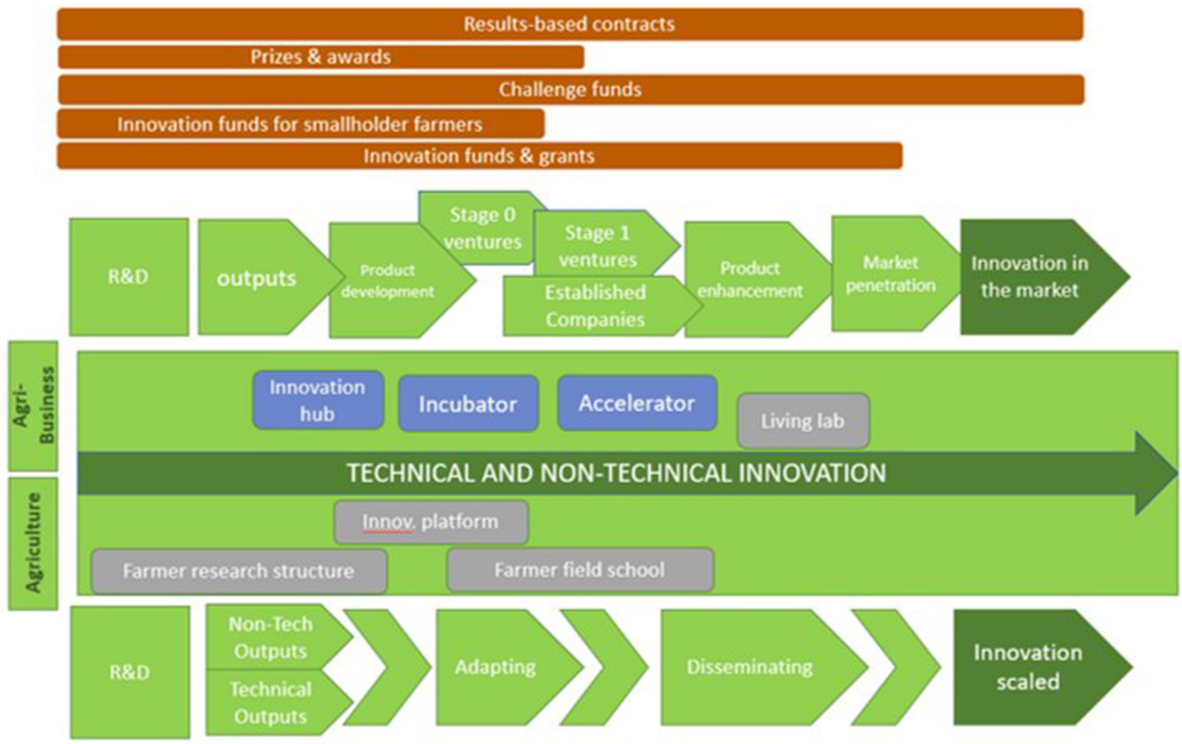


FIGURE 1
Position of innovation instruments within the agricultural sector and along the innovation continuum (Type A in blue, Type B in brown and Type C in gray).

2020; Richardson et al., 2021); and local agricultural research committees (CIALs), a farmer-run research service accountable to the local community (Polar et al., 2012). Finally, farmer field schools (FFSs) are a form of adult education, widely used in Africa and Asia, that aims to empower farmers and improve agricultural outcomes through agricultural knowledge exchange (Waddington and White, 2014; SSMP, 2016; Mariyono, 2019). The International Fund for Agricultural Development (IFAD) adapted the approach and introduced Livestock FFSs in East and Southern Africa—integrating active experimentation and *learning by doing* (Jordans, 2021). These instruments all involve users (and could be designed to be more user-driven), with the user generally being a farmer or community member. Most require that innovators have access to financial resources that can support innovation activities because their focus is on strengthening social and human capital.

Comparison of different instruments

The extent to which instruments were found to have contributed to inclusive development and fostered the uptake of research outputs or innovations is documented here. These are key factors that can contribute to supporting the strengthening and sustainability of agri-food systems.

Contribution to inclusive development

If addressed in the design, then many of the instruments can ensure inclusive or equitable development, specifically giving agency to marginalized actors (Mungai et al., 2019). For example, considering language and regional characteristics such as livelihood activities and access to natural resources and technology when designing innovation platforms (Masi, 2016). However, they need to be facilitated to prevent domination by certain groups of actors who wish to dictate the research agenda (Boogard et al., 2013). Some accelerators, innovation hubs, challenge funds, living labs and innovation funds and grants have specifically targeted women and youth, for example with their eligibility criteria (Tjornbo and Westley, 2012; Adekunle and Fatunbi, 2013; Pompa, 2013; Musikoyo et al., 2017; Cohen S. L. et al., 2019; IFAD, 2020). Additionally, there are incubators that monitor their portfolio to ensure that women-founded ventures are represented (InfoDev, 2011). However, open application processes and the costing models adopted by some facilities may still exclude the marginalized (Friederici, 2018). Innovation grants that enable proof-of-concept work by smaller companies (including startups) that would otherwise not be able to garner finance is another way of ensuring inclusive development (Howell, 2017). An alternative to financing innovation by marginalized groups is to finance innovation or outcomes that benefit marginalized groups—for example, gender-responsive innovation (Tambo, 2018) and results-based contracts that pay for addressing equity issues (Janus and Holzapfel, 2016). A key element that is promoted by a number of programs is to design the instruments to ensure that users are seen as equal to other participants (Nyström et al., 2014).

Several instruments center inclusiveness as a key intention, in particular IFSFs, FFSs and farmer research structures. A number of authors have confirmed that IFSFs can provide resources that allow the rural poor and vulnerable households to pilot their innovations and even patent them (Ashby et al., 2000; Friis-Hansen and Egelyng, 2007; Triomphe et al., 2012). FFSs and farmer research structures are also designed to allow for the participation of smallholder farmers, but may need to be designed to actively target marginalized groups, such as those with low literacy levels (Davis et al., 2010). Sometimes FRNs provide access to production assets that enable them to participate in innovation processes, but approaches such as iterative learning cycles are also important as they build farmers' capacities to engage effectively (Descheemaeker et al., 2021; Richardson et al., 2021).

Contribution to accelerating uptake of innovations and research outputs

Accelerating innovation uptake (i.e., achieving adoption of technologies/innovations) is mentioned in the literature as a key element of a number of instruments, namely incubators, accelerators, innovation hubs, IFSFs, innovation platforms and farmer research structures. Incubators and accelerators create links between innovators/entrepreneurs and companies that may wish to invest in or purchase the innovations (InfoDev, 2014; Hjortsø et al., 2017). Some facilities are linked to educational/research organizations and focus specifically on commercializing research and development outputs (InfoDev, 2011). It is expected that since potential users are involved in vetting applications submitted to IFSFs, they are likely to be addressing real needs, which will foster uptake (Ashby et al., 2000)—even more so if linkages are brokered with the private sector (Friis-Hansen and Egelyng, 2007; Triomphe et al., 2012). The co-development of innovations through innovation platforms generates a sense of ownership of the developed innovations, which has been found to foster research uptake. This can be further supported by non-research actors that disseminate the innovations (Agboton et al., 2018). Besides creating a sense of ownership, field visits, mini-workshops and focus group discussions on the program of a farmer research structure enable continuous evaluation and adaptation of technologies (Descheemaeker et al., 2021), while additional channels such as community radio and farmer-to-farmer exchanges can be used to disseminate results (and planting material) to other producers (CIAT, 2003; Kanoute et al., 2019).

While there is an expectation that challenge fund outcomes will be commercially viable with additional social and/or economic benefits (UNDP, 2016), there may be factors that prevent immediate uptake, and they may require third-party (such as government) intervention to make them affordable (Tjornbo and Westley, 2012). Sometimes, instruments are designed to improve communication between actors in order to foster uptake, as has been the case with certain innovation funds and grants (Rajalahti and Larson, 2011). Similarly, some programs that make use of prizes and awards (such as AgResults) include a cost-share element to create market stability and reduce costs for the end user, thereby accelerating uptake (Hammond et al., 2021). An important finding from programs using FFSs is that dissemination of information and technologies beyond the participating farmers is not always effective because uptake is strongly linked to experiential learning [ICIMOD (SMMP), 2008; Waddington and White, 2014; Goldstein, 2020]. Furthermore, it should be recognized that while uptake is the intention, technologies often cannot be shared as standardized practices because they may not be appropriate for all farmers, even within the same locality (Bakker et al., 2021).

There was little literature about the contribution of results-based contracts and living labs toward accelerating uptake. However, with living labs, market participation and business development that create linkages between companies and users may allow them to access markets (Masi, 2016; Musikoyo et al., 2017).

Recommendations for selection and use

The choice of instrument must consider the context in which it is to be used—which may or may not be that in which it has previously been used—followed by systematically considering the purpose and desired scale of investment and impact. It is recommended that this process be guided by the following considerations to ensure this and promote inclusive development and sustainability.

Matching the mandate of the program or organization

Some instruments specifically aim to support innovation by entrepreneurs (Type A), while others aim to contribute to broader human wellbeing. For example, challenge funds generally focus on global or societal issues related to human or environmental wellbeing, while some innovation hubs and incubators focus on translating research outputs into socio-economic impacts.

Positioning within the agricultural sector

An innovation manager may be mandated to target a specific part of the agricultural sector (primary production or processing) or type of farmer. Instruments differ in terms of their application to different parts of the sector. For example, prizes have been awarded to local innovators in rural contexts, small-scale commercial farmers, startup enterprises, large-scale commercial farmers, and even large agribusinesses, whereas FFSs generally focus on small-scale commercial farmers.

Ensuring sustainability

To achieve sustainability, instruments need to be institutionalized within government departments or other organizations' work programs or policies, because their use is often limited to project timeframes—especially projects funded by external donors (Anchala et al., 2005; Seifu et al., 2020). This situation demands changes in terms of organizational mandates and job descriptions. Alternatively, a strong business model is required that considers the capacity of the participants to pay for services, thereby ensuring continuity of these types of instruments.

Understanding the needs of smallholder farmers

The heterogeneity of smallholder farmers must be recognized so that efforts are made to include less literate and poorer segments of the community. It must also be noted that technologies developed with farmers in one locality may not necessarily be appropriate for those in another area, and they may also require new institutional arrangements.

Establishing the right stakeholder mix

With instruments that bring stakeholders together or broker linkages, it is important to have the correct mix of actors. This includes a strong facilitator who can manage power dynamics, and consideration for how the benefits will be felt by all to ensure participation.

Concluding discussion and final remarks

This study represents one of a handful that have recently compared the use of multiple instruments across multiple continents in the Global South, and can thus serve to provide comparative evidence to investors and funders to guide their decision making around, and awareness of, the potential challenges that need to be considered when selecting and designing instruments for use in specific contexts. However, a transition within the research and innovation landscape toward mainstreaming these instruments requires policy changes (e.g., to put funds directly in hands of farmers) and capacity building efforts within relevant organizations (e.g., developing facilitation skills).

While the comparative approach adopted in this study is valuable in terms of surfacing lessons to guide innovation managers and funders, it is extremely challenging because of the high levels of variability with which instruments have been designed, applied and evaluated. There is, therefore, a need for more structured and consistent monitoring and evaluation of the various costs associated with using the different instruments against the benefits that are derived, in order to provide evidence that these instruments are more effective than conventional research and extension instruments in achieving effective uptake and scaling of new innovations. Despite the limitations of this study and evident gaps in the body of literature reviewed, there clearly exists a range of instruments that can support innovation for inclusive development as well as fostering uptake. These simply require substantial thought regarding their design if they are to have the intended impacts.

Author contributions

BL, TH, and S contributed to conception and design of the study. SM and TN reviewed literature and organized the database. SR, JZ, and DT were involved in execution of the study. IA-F provided strategic guidance to the study. BL wrote the first draft of the manuscript. All authors contributed to manuscript revision.

Funding

This study was funded by the Commission on Sustainable Agriculture Intensification (CoSAI).

Acknowledgments

Based on a research project conducted on behalf of the Commission on Sustainable Agriculture Intensification (CoSAI) (Letty et al., 2021).

Conflict of interest

Authors BL, SM, TN, and S were employed by Institute of Natural Resources. Author DT was employed by Agribio Services. Author IA-F was employed by Forum for Agricultural Research in Africa (FARA).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1013156/full#supplementary-material

References

Adekunle, A. A., and Fatunbi, A. O. (2013). The concept of innovation funds for agricultural transformation (IFAT). *World Appl. Sci. J.* 6, 787–795. doi: 10.5829/idosi.wasj.2013.22.06.1132

Agboton, S. M., Sewade, P. L., and Ayenan, M. A. T. (2018). Successes and challenges in tackling constraints in soybean processing through multi-stakeholder innovation platforms in Agricultural Research for Development: evidence from the Consortium Soja du Bénin. *Afr. J. Rural Dev.* 3, 579–59.

Anchala, C., Deressa, A., Admasu, H., and Habte, E. (2005). "Enhancing innovations through Farmer Research Groups (FRGs): Basic concepts and experience in other countries," in *Farmer research group (FRG): Concept and practices. Proceedings of a Workshop* (Marc, Melkassa). Available online at: https://www.jica.go.jp/project/ethiopia/5065025E0/05/pdf/proceedings.pdf (accessed October 20-21, 2004).

Andersson, J., Norén, J., and Christoplos, I. (2014). *The Evaluation of the Challenge Fund Innovations Against Poverty, IAP*. Sida Decentralised Evaluation 2014:40. Stockholm, Sweden: Swedish International Development Cooperation Agency. Available online at: https://cdn.sida.se/publications/files/sida61781en-the-evaluation-of-the-challenge-fund-innovations-against-poverty-iap---final-report.pdf (accessed August 3, 2022).

Ashby, J. A., Braun, A. R., Gracia, T., del Pilar Guerrero, M., Hernández, L. A., Quiros, C. A., et al. (2000). *Investing in Farmers as Researchers: Experience with Local Agricultural Research Committees in Latin America*. Cali, Colombia: Centro Internacional de Agricultura Tropical (CIAT). Available online at: http://ciat-library.ciat.cgiar.org/articulos_ciat/Investing_farmers.pdf (accessed August 3, 2022).

Bakker, T., Dugue, P., and de Tourdonnet, S. (2021). Assessing the effects of farmer field schools on farmers' trajectories of change in practices. *Agron. Sust. Dev.* 41, 18. doi: 10.1007/s13593-021-00667-2

Beesabathuni, K., Askari, S., Bajoria, M., Bloem, M., Gavin-Smith, B., Hamirani, H., et al. (2021). *Food Systems Innovation Hubs in Low-and-Middle-Income Countries*. Food Systems Summit Brief prepared by Research Partners of the Scientific Group for the Food Systems Summit. Available online at: https://sc-fss2021.org/wp-content/uploads/2021/04/FSS_Brief_Food_Systems_Innovation_Hubs.pdf (accessed March 26, 2021).

Boogard, B. K., Schut, M., Klerkx, L., Leeuwis, C., Duncan, A., and Cullen, B. (2013). *Critical Issues for Reflection when Designing and Implementing Research for Development in Innovation Platforms*. Wageningen, The Netherlands: Wageningen University and Research Centre. Available online at: https://hdl.handle.net/10568/35028 (accessed August 3, 2022).

Brookfield Institute (2018). *Exploring Policy Innovation: Tools, Techniques and Approaches*. Toronto, Canada: Brookfield Institute. Available online at: https://brookfieldinstitute.ca/exploring-policy-innovation (accessed August 3, 2022).

Butler, J. R. A., Darbas, T., Addison, J., Bohensky, E. L., Carter, L., Cosijin, M., et al. (2017). "A hierarchy of needs for achieving impact in international research for development," in *Social Science and Sustainability*, eds H. Schandl and I. Walker (Melbourne, VIC, Australia: CSIRO Publishing), 109–129.

CIAT (2003). *Farmer research group dynamics in eastern Africa. Highlights CIAT in Africa*. Cali, Colombia: Centro Internacional de Agricultura Tropical. Available online at: http://ciat-library.ciat.cgiar.org/articulos_ciat/highlight8.pdf (accessed June 08, 2003).

Cohen, S., Fehder, D. C., Hochberg, Y. V., and Murray, F (2019). The design of start-up accelerators. *Res. Policy* 48, 1781–1797. doi: 10.1016/j.respol.2019.04.003

Cohen, S. L., Bingham, C. B., and Hallen, B. L. (2019). The role of accelerator designs in mitigating bounded rationality in new ventures. *Administr. Sci. Quart.* 64, 810–854. doi: 10.1177/0001839218782131

Cooke, S. J., Venturelli, P., Twardek, W. M., Lennox, R. J., Brownscombe, J. W., Skov, C., et al. (2021). Technological innovations in the recreational fishing sector: implications for fisheries management and policy. *Rev. Fish Biol. Fish.* 31, 253–288. doi: 10.1007/s11160-021-09643-1

Cunningham, P., and Cunningham, M. (2016). *Report on Innovation Spaces and Living Labs in IST-Africa Partner Countries*. IST-Africa Consortium. Available online at: http://ist-africa.org/home/files/IST-Africa_InnovationSpaces_LL_v2_310116.pdf (accessed August 3, 2022).

Davis, K., Nkonya, E., Kato, E., Mekonnen, D. A., Odendo, M., Miiro, R., et al. (2010). *Impact of farmer field schools on agricultural productivity and poverty in East Africa*. IFPRI Discussion Paper 00992. Washington, DC, USA: International Food Policy Research Institute. Available online at: https://ifpri.org/publication/impact-farmer-field-schools-agricultural-productivity-and-poverty-east-africa (accessed August 3, 2022).

de Koning, S., de Haas, W., de Roo, N., Kraan, M., and Dijkshoorn-Dekker, M. (2021). *Tools for transitions: An inventory of approaches, methods and tools for stakeholder engagement in developing transition pathways to sustainable food systems*. Wageningen Marine Research report C001/21. Wageningen, The Netherlands: Wageningen University and Research. Available online at: https://library.wur.nl/WebQuery/wurpubs/fulltext/538961 (accessed August 3, 2022).

Deloitte (2015). *The Many Ways to Pay for Results, Funding options for innovation and success*. Deloitte Development LLC. Available online at: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/public-sector/us-federal-the-many-ways-to-pay-for-results.pdf (accessed August 3, 2022).

Descheemaeker, K., Huet, E., Dissa, A., Sanogo, O., Dembele, O., Doumbia, S., et al. (2021). *Farmer research networks for co-designing agro-ecological intensification options in crop-livestock systems of southern Mali*. International Symposium for Farming System Design. Available online at: https://edepot.wur.nl/545853 (accessed March 21–24, 2021).

Devaux, A., Torero, M., and Donovan, J. (2018). Agricultural innovation and inclusive value-chain development: a review. *J. Agribusiness Dev. Emerg. Econ.* 8, 99–123. doi: 10.1108/JADEE-06-2017-0065

Fatunbi, A. O., Youdeowei, A., Ohiomoba, S. A., Adewale, A., and Akinbanijo, O. O. (2016). *Agricultural Innovation Platforms: Framework for Improving Sustainable Livelihoods in Africa.* Accra, Ghana: Forum for Agricultural Research in Africa. Available online at: https://library.faraafrica.org/2020/12/17/agricultural-innovation-platforms-framework-for-improving-sustainable-livelihoods-in-africa (accessed August 3, 2022).

Friederici, N. (2018). Grounding the dream of African innovation hubs: two cases in Kigali. *J. Dev. Entrepren.* 23, 1850012. doi: 10.1142/S1084946718500127

Friis-Hansen, E., and Egelyng, H. (2007). *Supporting local innovation for rural development. Analysis and review of five innovation support funds.* DIIS Report 2007:4. Copenhagen, Denmark: Danish Institute for International Studies. Available online at: https://orgprints.org/id/eprint/11304 (accessed August 3, 2022).

Fróna, D., Harangi-Rákos, M., and Szenderák, J. (2019). The challenge of feeding the world. *Sustainability* 11, 5816. doi: 10.3390/su11205816

Glover, D., Sumberg, J., Ton, G., Andersson, J., and Badstue, L. (2019). Rethinking technological change in smallholder agriculture. *Outlook Agric.* 48, 169–180. doi: 10.1177/0030727019864978

Goldstein, M. (2020). *The friends of my friends... don't know much about composting.* World Bank Blogs. Available online at: https://blogs.worldbank.org/impactevaluations/friends-my-friendsdont-know-much-about-composting (accessed March 04, 2020).

Hammond, J. M., Maulidi, B., and Henning, N. (2021). Targeted FMD vaccines for Eastern Africa: the AgResults foot and mouth disease challenge project. *Viruses* 13, 1830. doi: 10.3390/v13091830

Hellin, J. (2012). Agricultural extension, collective action and innovation systems: Lessons on network brokering from Peru and Mexico. *J. Agric. Educ. Extens.* 8, 141–159. doi: 10.1080/1389224X.2012.655967

Hjortsø, C. N. P., Alexander, I. K., and Hernandez Chea, R. R. (2017). *Experiences and lessons learned from the UniBRAIN Agribusiness Incubation Programme.* IFRO Report No. 266. Copenhagen, Denmark: Department of Food and Resource Economics, University of Copenhagen. Available online at: https://static-curis.ku.dk/portal/files/188232225/IFRO_Report_266.pdf (accessed August 3, 2022).

Homann-Kee Tui, S., Adekunle, A., Lundy, M., Tucker, J., Birachi, E., Schut, M., et al. (2013). *What are innovation platforms?* Innovation Platforms Practice Brief 1. Nairobi, Kenya: International Livestock Research Institute. Available online at: http://oar.icrisat.org/id/eprint/7343 (accessed August 3, 2022).

Howell, S. T. (2017). Financing innovation: evidence from R&D grants. *Am. Econ. Rev.* 107, 1136–1164. doi: 10.1257/aer.20150808

ICIMOD (SMMP) (2008). *Natural Resource Management Approaches and Technologies in Nepal: Approach – Farmer Field Schools on Integrated Plant Nutrient Systems.* Available online at: https://issuu.com/wocat/docs/nepcat/121 (accessed August 3, 2022).

IFAD (2020). *Corporate-Level Evaluation IFAD's support to innovations for inclusive and sustainable smallholder agriculture.* Independent Office of Evaluation. ISBN 978-92-9266-035-2. Available online at: https://www.ifad.org/en/web/ioe/-/corporate-level-evaluation-on-ifad-s-support-to-innovations-for-inclusive-and-sustainable-smallholder-agricultu-1 (accessed August 3, 2022).

InfoDev (2011). *Growing Food, Products, and Businesses: Applying Business Incubation to Agribusiness SMEs.* Washington, DC, USA: The World Bank. Available online at: https://openknowledge.worldbank.org/bitstream/handle/10986/23038/100351.pdf?sequence=4&isAllowed=y (accessed August 3, 2022).

InfoDev (2014). *Villgro Incubator – India Case Study.* Washington, DC, USA: The World Bank. Available online at: https://openknowledge.worldbank.org/bitstream/handle/10986/20110/901300WP0Box380.villgro.india0.web0.pdf?sequence=1&isAllowed=y (accessed August 3, 2022).

Janus, J., and Holzapfel, S. (2016). *Results based approaches in agriculture: What is the potential?* Discussion Paper 25/2016. Bonn, Germany: German Development Institute. Available online at: https://die-gdi.de/uploads/media/DP_25.2016.pdf (accessed August 3, 2022).

Jiménez, A., and Zheng, Y. (2021). Unpacking the multiple spaces of innovation hubs. *Inform. Soc.* 37, 163–176. doi: 10.1080/01972243.2021.1897913

Jordans, E. (2021). *IFAD – Stock-taking exercise Livestock Farmer Field Schools (L-FFS), East and Southern Africa.* Report not available for circulation.

Kaimowitz, D. (ed.) (1990). *Making the Link: Agricultural Research and Technology Transfer in Developing Countries.* New York, NY, USA: CRC Press.

Kanoute, A., Diakite, B., Diarra, S., Traore, S. and Timbely, D. (2019). *Stimulating mutual learning through agro-ecological experiments, Networking experience based on joint experiments and thesupport funds for local innovations in the regions of Ségou and Mopti.* Available online at: https://www.kit.nl/wp-content/uploads/2019/11/Stimulating-mutual-learning-through-agro-ecological-experiments-1.pdf (accessed August 3, 2022).

Kavoi, J. M., Mwangi, J. G., and Kamau, G. M. (2014). Factors related to the low uptake of technologies and innovations in semi-arid areas of lower eastern Kenya. *Agric. Soil Sci.* 1, 12–21. Available online at: https://www.researchgate.net/publication/270512619_Factors_Related_to_the_Low_Uptake_of_Technologies_and_Innovations_in_Semi-Arid_Areas_of_Lower_Eastern_Kenya (accessed November 25, 2022).

Letty, B., Hart, T., Murugan, S., Naidoo, T., Rai, S., Zake, J., et al. (2021). *Effective Approaches and Instruments for Research and Innovation for Sustainable Agri-Food Systems.* Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://wle.cgiar.org/cosai/approaches-and-instruments (accessed August 3, 2022).

Mariyono, J. (2019). Farmer training to simultaneously increase productivity of soybean and rice in Indonesia. *Int. J. Prod. Perform. Manag.* 68, 1120–1140. doi: 10.1108/IJPPM-10-2018-0367

Masi, S. D. (2016). Social labs: identifying Latin American Living Labs. *Hum. Soc. Sci.* 4, 76–82. doi: 10.11648/j.hss.20160403.12

McNicholl, D., Hope, R., Money, A., Lane, A., Armstrong, A., Dupuis, M., et al. (2020). *Results-based contracts for rural water services.* Uptime Consortium Working Paper Vol. 2. Oxford, UK: Smith School of Enterprise and the Environment, University of Oxford. Available online at: https://static1.squarespace.com/static/5d5fc19961d87c00011689d2/t/5f1759127e30ed322cd5dba0/1595365662058/Results-Based+Contracts+for+Rural+Water+Services.pdf (accessed August 3, 2022).

Mungai, P., Jimenez, A., Kleine, D., and Van Belle, J. (2019). "The role of the marginalized and unusual suspects in the production of digital innovations: models of innovation in an African context In Locally Relevant ICT Research," in *10th International Development Informatics Association Conference*, eds K. Krauss, M. Turpin, and F. Naude (Tshwane, South Africa: IDIA). doi: 10.1007/978-3-030-11235-6_17

Musikoyo, K., Wambalaba, F., Peterson, C., and Asena, S. (2017). *Expanding business opportunities for youth in the fish and poultry sectors in Kenya.* Final Technical Report. Nairobi, Kenya: United States International University-Africa. Available online at: http://hdl.handle.net/10625/56863 (accessed August 3, 2022).

Navarette, I., Lopez, V., Andrade-Piedra, J., Almekinders, C., and Struik, P. (2020). *What can we learn by implementing farmers' research networks to investigate on-farm management practices?* Available online at: https://www.ccrp.org/wp-content/uploads/2020/08/Navarrete-What-can-we-learn-by-implementing-farmers%E2%80%99s.pdf (accessed August 3, 2022).

Nyström, A.-G., Leminen, S., Westerlund, M., and Kortelainen, M. (2014). Actor roles and patterns influencing innovation in living labs. *Indus. Market. Manag.* 43, 483–495. doi: 10.1016/j.indmarman.2013.12.016

OECD and European Commission (2019). *Policy brief on incubators and accelerators that support inclusive entrepreneurship.* Policy Brief. Paris, France: Organisation for Economic Co-operation and Development. Available online at: https://oecd-ilibrary.org/docserver/d7d81c23-en.pdf (accessed August 3, 2022).

Organisation for Economic Cooperation and Development/Statistical Office of the European Communities (OECD/Eurostat) (2005). *The Measurement of Scientific and Technological Activities - Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data, 3rd Edn.* Paris: OECD/Eurostat.

Polar, V., Fernández, J., Ashby, J., Quiro, C. A., and Roa, J. I. (2012). *Participatory methods and the coproduction of agricultural advisory services: Results from four case studies in Bolivia and Colombia.* CIP Social Sciences Working Paper No. 2012-1. Lima, Peru: International Potato Center. Available online at: https://hdl.handle.net/10568/90952 (accessed August 3, 2022).

Pompa, C. (2013). *Understanding challenge funds.* ODI Report. London, UK: Overseas Development Institute. Available online at: https://cdn.odi.org/media/documents/9086.pdf (accessed August 3, 2022).

Rajalahti, R., and Larson, G. (2011). *Agricultural innovation funds.* Agriculture and Rural Development Notes No. 55. Washington, DC, USA: The World Bank. Available online at: https://hdl.handle.net/10986/9453 (accessed August 3, 2022).

Richardson, M., Coe, R., Descheemaeker, K., Haussman, B., Wellard, K., Moore, M., et al. (2021). Farmer research networks in principle and practice. *Int. J. Agric. Sust.* 20, 247–264. doi: 10.1080/14735903.2021.1930954

Robles, A. G., Hirvikoski, T., Schuurman, D., and Stokes, L. (2015). *Introducing ENoLL and its Living Lan Community.* European Network of Living Labs. Available online at: https://issuu.com/enoll/docs/enoll-print (accessed August 3, 2022).

Samberg, L. H., Gerber, J. S., Ramankutty, N., Herrero, M., and West, P. C. (2016). Subnational distribution of average farm size and smallholder contributions to global food production. *Environ. Res. Lett.* 11, 124010. doi: 10.1088/1748-9326/11/12/124010

Seifu, M., van Paassen, A., Klerkx, L., and Leeuwis, C. (2020). Anchoring innovation methodologies to 'go-to-scale'; a framework to guide agricultural research for development. *Agric. Syst.* 182, 102810. doi: 10.1016/j.agsy.2020.102810

SSMP (2016). *Natural Resource Management Approaches and Technologies in Nepal: Approach – Farmer Field Schools on Integrated Plant Nutrient Systems*. Available online at: https://www.icimod.org/solutions/farmer-field-schools-on-integrated-plant-nutrient-systems/ (accessed August 3, 2022).

Tambo, J. A. (2018). Recognizing farmer-generated innovations through contests: insights from four African countries. *Food Security* 10, 1237–1250. doi: 10.1007/s12571-018-0835-y

Tjornbo, O., and Westley, F. R. (2012). Game changers: the big green challenge and the role of challenge grants in social innovation. *J. Soc. Entrepren.* 3, 166–183. doi: 10.1080/19420676.2012.726007

Trémolet, S. (2015). *Can Innovation Prizes help address water and sanitation challenges? Ideas to Impact Publication*. London, UK: UK Department for International Development. Available online at: https://assets.publishing.service.gov.uk/media/5f021d7f3a6f4023d04934e3/Can_innovation_prizes_help_address_water_and_sanitation_challenges.pdf (accessed August 3, 2022).

Triomphe, B., Wongtschowski, M., Waters-Bayer, A., Lugg, D., and van Veldhuizen, L. (2012). *Module 5: Innovative activity Profile 4: Providing farmers with direct access to innovation funds*. Available online at: https://www.semanticscholar.org/paper/Module-5%3A-innovative-activity-profile-4%3A-providing-Triomphe-Wongtschowski/8c4b03d1a5ea8c4fefd79d84eb8f04b02dbedc34 (accessed August 3, 2022).

UNDP (2016). *Enterprise Challenge Fund*. New York, NY, USA: United Nations Development Programme. Available online at: https://sdfinance.undp.org/content/sdfinance/en/home/solutions/enterprise-challenge-fund.html (accessed August 3, 2022).

UNESCO (2019). *Campos dos Goytacazes Innovation Hub*. UNESCO-UNEVOC Promising Practice in Focus 2019. New York, NY, USA: United Nations Educational, Scientific and Cultural Organization. Available online at: https://unevoc.unesco.org/pub/promisingpractices-picg-en_final.pdf (accessed August 3, 2022).

van Gent, S. (2017). *Beyond buzzwords: What is "Inclusive Development"?* Synthesis Report. INCLUDE Knowledge Platform on Inclusive Development Policies. Available online at: https://includeplatform.net/wp-content/uploads/2017/09/Beyond-buzzwords.pdf (accessed August 3, 2022).

Waddington, H., and White, H. (2014). *Farmer field schools from agricultural extension to adult education*. 3IE Systematic Review Summary 1. New Delhi, India: International Initiative for Impact Evaluation. Available online at: https://3ieimpact.org/evidence-hub/publications/systematic-review-summaries/farmer-field-schools-agricultural-extension (accessed August 3, 2022). doi: 10.23846/SRS001ffs

WUR (2021). First *Eastern African food-systems oriented living lab opens*. Wageningen, The Netherlands: Wageningen University and Research. Available online at: https://wur.nl/en/newsarticle/First-Eastern-African-food-systems-oriented-living-lab-opens.htm (accessed August 3, 2022).

frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 18 January 2023
DOI 10.3389/fsufs.2022.1039962

OPEN ACCESS

EDITED BY
P. V. Vara Prasad,
Kansas State University, United States

REVIEWED BY
Humnath Bhandari,
International Rice Research Institute, Bangladesh

*CORRESPONDENCE
Molly E. Brown
mbrown52@umd.edu
Ignacio A. Ciampitti
ciampitti@ksu.edu

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 08 September 2022
ACCEPTED 28 December 2022
PUBLISHED 18 January 2023

CITATION
Brown ME, Carcedo AJP, Eggen M, Grace KL, Neff J and Ciampitti IA (2023) Integrated modeling framework for sustainable agricultural intensification. *Front. Sustain. Food Syst.* 6:1039962. doi: 10.3389/fsufs.2022.1039962

Integrated modeling framework for sustainable agricultural intensification

Molly E. Brown[1]*, Ana J. P. Carcedo[2], Michael Eggen[3], Kathryn L. Grace[4], Jason Neff[3] and Ignacio A. Ciampitti[2]*

[1]Department of Geographical Sciences, University of Maryland College Park, College Park, MD, United States, [2]Department of Agronomy, Kansas State University, Manhattan, KS, United States, [3]Environmental Studies Program, Mortenson Center in Global Engineering, University of Colorado, Boulder, CO, United States, [4]Department of Geography, Environment, and Society and Minnesota Population Center, University of Minnesota, Minneapolis, MN, United States

Agricultural scientists are pursuing sustainable intensification strategies to increase global food availability, but integration from research to impact at the local-level requires knowledge of demographic and human-environment to enhance the adaptive capacity of farmers cultivating <10 ha. Enhancing close collaboration among transdisciplinary teams and these smallholders is critical to co-elaborate policy solutions to ongoing food security crises that are likely to be attuned with local conditions. Human and socio-cultural aspects need to be considered to facilitate both adoption and dissemination of adapted management practices. Despite this well-known need to co-produce knowledge in human systems, we demonstrate the inequality of current agricultural research in smallholder farming systems with heavy focus on a few domains of the sustainable intensification agricultural framework (SIAF), ultimately reducing the overall impact of interventions due to the lack compatibility with prevailing social contexts. Here we propose to integrate agriculture and agronomic models with social and demographic modeling approaches to increase agricultural productivity and food system resilience, while addressing persistent issues in food security. Researchers should consider the scale of interventions, ensure attention is paid to equality and political processes, explore local change interactions, and improve connection of agriculture with nutrition and health outcomes, *via* nutrition-sensitive agricultural investments.

KEYWORDS

integrated modeling, demography, sustainable agriculture, framework, agronomy

1. Introduction

Globally, agricultural production occurs at vastly different scales, from massive corporate or government owned industrial agricultural farms to small-scale farmers working to produce sufficient food for their families. These small-scale farmers cultivating <10 ha (referred to hereafter as smallholders), often have access to the fewest technologies and financial safety-nets but still produce close to 30% of the world's food

(Ricciardi et al., 2018). Here we propose an **enhanced, quantitative engagement of agronomists and agricultural development experts with health and social science communities** to consider the needs, desires, and behaviors of individuals alongside strategies to increase yields and reduce human labor inputs to quantify context and barriers to agricultural adoption. By incentivizing researchers to extend agricultural technical and conceptual approaches (hereafter ag-approaches) developed in agriculture science to the impacts experienced by households and individuals, we can accelerate the transformation of the global food system (Pretty, 1997).

Farmers employ countless management strategies to hedge some of the risk inherent in areas dependent on variable rainfall or other weather hazards (Bhatta and Aggarwal, 2016; Sibhatu and Qaim, 2017). These strategies are often based on tradition or experience which may, or may not, align with existing scientific knowledge on how to adapt to rapidly changing conditions. Unanticipated and unmitigated climate risk is a primary driver of both short- and long-term food insecurity, as it reduces uptake of new agricultural technologies and can lead to negative livelihood impacts well after a period of climatic stress (Hansen et al., 2022).

There are many ways to develop specific policies that support the transformation of climate information into multi-layered agricultural programs, including anticipatory action and index-based insurance which supports governments and individuals in adopting new agricultural practices (Hansen et al., 2022). For example, the World Food Program's R4 Rural Resilience Initiative provides access to subsidized drought and flood risk insurance products which are triggered with a precipitation index. The program allows vulnerable households to access agricultural insurance while supporting community-led disaster risk reduction and landscape restoration activities (Spiegel and Satterthwaite, 2013). Connecting agricultural technologies to insurance, increased yield or other development goals requires rigorous modeling and assessments of social, economic and productivity outcomes. However, many of these programs offload assessment of performance of their program to models of their choosing, without rigorous insight into their quality, relevance, or connection to livelihood improvements (Saltelli et al., 2020). The failure of agricultural development programs may come from incomplete model selection, unfounded assumptions, lack of quality or quantity of relevant local data, or lack of insight into the context in which the implementation may occur.

Agronomists and agricultural development entities are doing vital work on developing new, high yielding varieties and agricultural management strategies to more sustainably increase agricultural productivity. These agricultural interventions are being developed with a focus on environmental sustainability (Rockström et al., 2017; Pretty et al., 2018; Peng et al., 2020; Pilling et al., 2020). Ag-approaches can be used to understand how transformation of heterogeneous smallholder systems into those that regularly and consistently produce marketable food and sustainable rural livelihoods can be achieved. Increased agricultural production through intensification needs to be balanced with environmental and social considerations (Hoffmann et al., 2015). Despite impressive technical advancements made in agronomy expertise, downstream impacts on people's lives are difficult to consistently achieve and document, especially in low-income settings (Di Prima et al., 2022). Only a few examples have been documented on communities that have been able to attain long-term behavioral change in smallholder farm management (Cui et al., 2018; Stevenson et al., 2019), despite decades of investment. This is worsened by the critical lack of ground data observations (Saltelli et al., 2020) of agroecological and socioeconomic heterogeneity of smallholders needed to tailor farming practices, as not all practices are universally beneficial (Stevenson et al., 2019).

Social considerations, such as attitudes, preferences, and behaviors of stakeholders in rural areas dominated by smallholder agriculture livelihoods need to be examined while researching sustainable agriculture interventions (Ban et al., 2013). Stakeholders within agriculture settings include not only farmers and their families, but also the community, retailers, input providers, wholesalers and consumers (Brown et al., 2022). Explicitly considering stakeholders during research and planning of sustainable agriculture interventions should allow any suggested interventions to be more realistic and inclusive, informing complex choices by farmers on which crops (Lemos and Morehouse, 2005), with what inputs and with how much investment (Hirsch et al., 2011).

Ag-approaches are integral to developing policy-relevant scenarios to understand the impact of interventions like climate services (Hansen et al., 2007), ag-tech tools (Oyinbo et al., 2020), or agricultural insurance (Osgood et al., 2018). Farm management components that include both tactical and operational decision-making (Fountas et al., 2006) represent key factors where interventions and investments can be planned. Nevertheless, as Siddique et al. (2012) points out, much of the knowledge derived from agronomic crop science has often resulted in reductionist approaches to agricultural management, where a single management factor is modified which results in yield or crop quality improvements. Multiple factors across diverse settings are rarely managed and modified together in ways that simulate the complexity of smallholder systems. If farmers are to benefit from agronomic crop science focused on sustainability, it must be integrated into an overall crop management process, accounting for interactions between factors and incorporation of human, social and economic constraints.

1.1. Modeling sustainable intensification

Integrated social and economic models focus on sustainably increasing productivity to produce more food per unit of land (Velten et al., 2015). Although there has been significant effort on sustainable intensification frameworks (Zurek et al., 2016), food security and nutrition (Fanzo et al., 2016), and socioeconomic factors driving food provisioning in smallholder systems (Ritzema et al., 2017), there currently isn't an integrating framework that brings the pieces together to address food security across diverse agroecosystems. This gap is particularly notable because increased yields may not actually result in increased consumption of protein and micronutrients in low-income populations (Firbank, 2012). Moreover, a singular focus on yields (or nutrition alone) can result in unintended consequences including increased environmental and/or social impacts in these deeply integrated socio ecological systems (Zurek et al., 2016). These issues may be intensified because climate variability and change has the potential to transform and degrade agricultural systems if not incorporated and planned for through a wide range of policy, economic, and social system levers (Hansen et al., 2022).

Musumba et al. (2017), proposed five domains (productivity, economic, environment, human condition, and social) to provide indicators for assessing the relative sustainability of an agricultural innovation. To develop innovations with a balanced approach across domains, research needs to be interdisciplinary, yet the lack of integration is conspicuous among Ag-innovations. Researchers working in sustainable development need to more strongly consider non-environmental aspects to agricultural intensification such as social issues, economics (Zurek et al., 2016) issues of equity, poverty alleviation, and gender empowerment (Loos et al., 2014). In the next two sections, we present a review of the literature and the results which provide insight as to how well the sustainable agriculture literature has been able to engage with all five domains. We then proceed to propose a more integrated system that may result in improved outcomes.

2. Methods

We conducted two literature reviews focused on representing the most influential knowledge about agricultural interventions. We identify the most cited 50 publications and the most relevant 50 papers of the last 5 years using the methodology of Nagendra et al. (2018). Our objectives were to synthesize the literature on interventions in smallholder farming systems, and to summarize the current state of knowledge and identify the different domains from the Sustainable intensification Assessment Framework (SIAF) (Musumba et al., 2017; Stewart et al., 2018).

A search was conducted on April 21st, 2022 in the Web of Science database using the keywords *"Interventions," "Innovations," "Agriculture," "Smallholders," "Food Security," "Sustainable Intensification," and "Modeling"*. The results were filtered according to the following criteria:

- Journal Citation Report from the top 50% (quartiles 1 and 2) to measure the probability that the article is influential.
- Article search results were filtered by "highly cited" as provided by the Web of Science, and then ordered in terms of relevance. Only the top 1,000 most highly cited papers were kept.
- From these papers, we then created two groups (1) most cited 50 papers most cited from the 1,000 subset, (2) last 5 years, first 50 papers by relevance from the last 5 years.
- Full-text screening of the 100 resulting papers was done to classify each into the five domains described by the Sustainable intensification Assessment Framework [The Five Domains | Sustainable Intensification Assessment Framework (SIIL) (sitoolkit.com)]. The Supplementary material provide the complete reference and number of citations in the Web of Science for each article.

To analyze the papers' contribution to interdisciplinary research on agriculture and nutrition, we evaluated the 100 papers on whether they included mention of the five domains of sustainable agriculture, as described below:

- Productivity, which focuses on intensification of agriculture by increasing the output per unit input per season or year;
- Economic, which focuses on issues directly related to the profitability of agricultural activities and return on investment;
- Environmental, which focuses on the natural resource base that supports agriculture, including soil, water, natural habitat, and the level of pollution of the surrounding ecosystem resulting from agriculture;
- Human, which pertains to the individual or household, including nutrition status, food security, and capacity to learn and adapt new ways of doing agriculture; and
- Social, which focuses on social interactions including inter-household and cross-social groups in a community or landscape, including the ability to manage conflicts related to agriculture and natural resource management (Musumba et al., 2017).

3. Literature review results

Figure 1 shows the lack of connection between research realms. There are significant connections between farming and

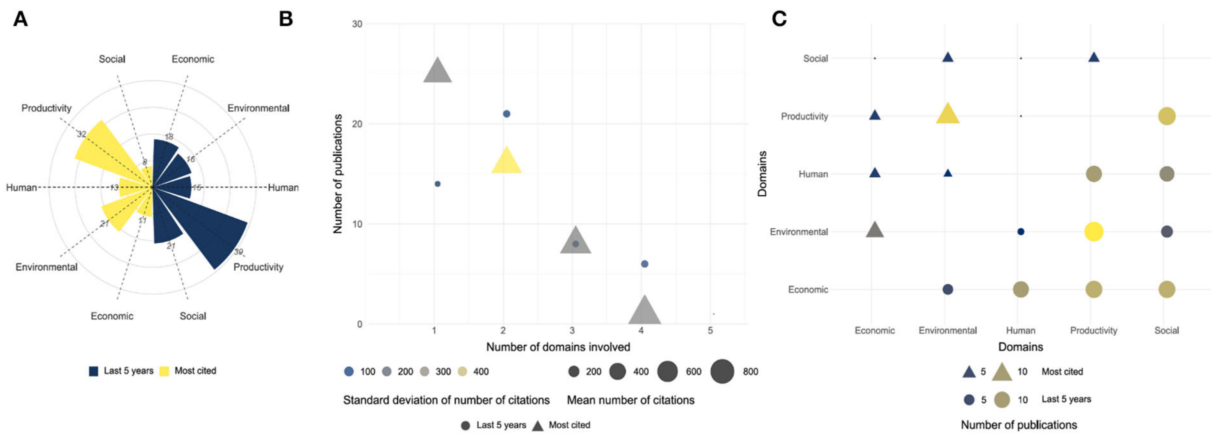


FIGURE 1
In a literature review capturing the 50 most highly cited and the 50 in the past 5 years, we show **(A)** the number of publications of each domain for the past 5 years (dark blue) and most cited (yellow); **(B)** the number of publications out of the 100 reviewed (y axis) plotted against the number of domains represented in each paper (x axis); and **(C)** the five different domains are plotted along a matrix, with the number of publications capturing multiple domains represented by the size and color of the symbol (yellow for most cited, black for publications from the past 5 years).

human nutrition, and therefore human health but only a few approaches have tried to capture this interaction (Moberg et al., 2020; Di Prima et al., 2022). Furthermore, most of the publications that involved human domain focused mainly on nutrition, and especially on the calories consumed, disregarding the true complexity of utilization and access to a balanced diet with sufficient micronutrients and diversity (Lobell and Gourdji, 2012; Hasegawa et al., 2018). Lastly, most of the publications, when they included a social assessment, focused on economic concepts of market access and supply chains (Figure 1C; Horbach et al., 2012; Garrett et al., 2017; Ceballos et al., 2020). While Ag-economists focus on the cost/benefit and risk assessments associated with adopting new ag-methods, this kind of agriculture-oriented research is not well connected to broader social science and public health research (Griscom et al., 2017; Meemken et al., 2019; Adegbeye et al., 2020). In summary, research in this domain has neglected the real intricacy of the connections between biological systems and demographic aspects.

4. Proposed framework

Researchers in social sciences and public health are considering the ways local food production impacts child health with a focus on expanding social science/health research in ways that consider the climate-food security linkage (Grace, 2017; Cooper et al., 2019). Anthropometric measurement (especially of children—e.g., stunting or wasting) allows for a quantitative assessment of an individual's health at the time of survey. From this information, researchers ascertain the level of undernourishment in a community and can use this information to spatially and temporally evaluate aspects of the food system that can be connected to biophysical data or agricultural models (Phalkey et al., 2015; Shively et al., 2015; Shively, 2017; Randell et al., 2021). Most studies that seek to connect environmental shocks and agriculture to human health use data (aggregated over space and time) on temperature, precipitation and vegetation anomalies, such as drought, heat waves and excessive rainfall (Brown et al., 2014; Randell and Gray, 2019; Sellers and Gray, 2019; Jain, 2020). Understanding how exposure to environmental shocks combined with the timing of exposure of individuals will help development programs to design appropriate interventions to protect human health and wellbeing (Grace et al., 2020; Hunter et al., 2021). This fairly general approach has been especially relevant in the context of climate change as scholars work to consider the linkage between the environment, food systems and health outcomes. However, the use of coarse environmental data fails to engage with the complexities and advancements in agronomic sciences and therefore misses an opportunity to advance cutting-edge science to support climate change adaptation.

A more robust alignment between agronomists and social science research communities is still needed to create more effective food system investments (Yaro, 2006). Here we propose **enhanced, quantitative engagement** that considers the needs, desires, and behaviors of individuals alongside strategies to increase yields and reduce human labor inputs to quantify context and barriers to agricultural adoption and connect them to food security outcomes. Therefore, we propose a new approach in agricultural, technical and conceptual research that links agriculture science to health, nutrition, and demographic impacts experienced by households and individuals. This can be achieved by encouraging researchers to Integrate

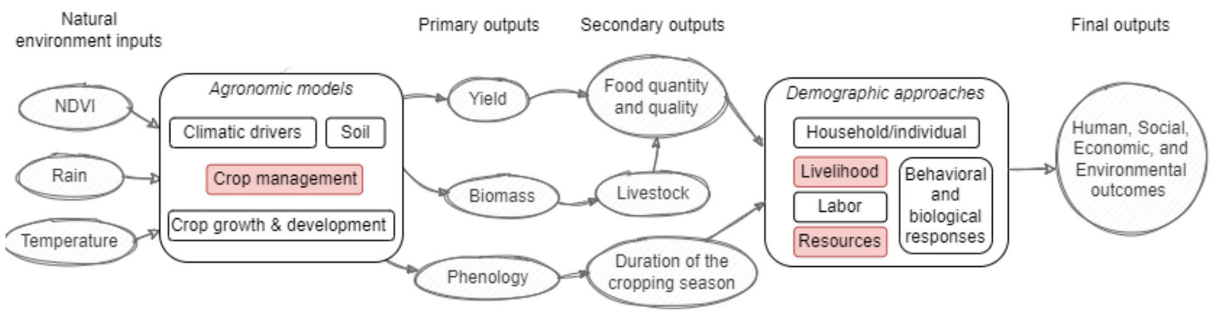


FIGURE 2
Traditional demographic approaches integrated with agronomic models. Inputs and outputs are represented by circles; models are represented by squares. Boxes within the models represent model components. Agronomic model components are a simplification of Keating et al. (2003). Demographic approaches components are a simplification of Grace (2017). Red boxes of crop management, labor, resources are all modeling inputs that are targets of direct investment by policy makers.

process-oriented crop models with demographic and health models that can enable exploration of the impacts of specific interventions through attention to the biophysical and field management aspects affecting food production (Figure 2).

5. Integrated frameworks

An integrated quantitative modeling framework that allows the use of information across all five domains in sustainable intensification will enable the identification of barriers, develop new insights and scenarios that could test the likely results of policy changes and intervention investments on food security and nutrition. Figure 2 shows how the community could use interdisciplinary engagement to accelerate planning for investments, highlighted in the models with red coloration. Primary outputs of crop models are estimates of crop yield and biomass at a certain site and year (Holzworth et al., 2018; Hoogenboom et al., 2019). From these, crop models can derive other outputs of interest to the food security community, including total calories, nutrient content, cost, and complexity of the agriculture system (Valin et al., 2014; Grafton et al., 2015). In this context, crop growth models arise as an effective tool to summarize how the biophysical environment affects a community, and focuses these results on human health information such as nutrition and health outcomes. By broadening the focus beyond process-based agronomic interventions, a more holistic approach can be promoted.

Integrated frameworks and models hold the promise to plan, implement and measure outcomes across a variety of contexts. Management factors in process-oriented Ag-Approaches are integral to developing policy-relevant scenarios to understand the impact of interventions and include crop and varietal choice, planting date, fertilizer and manure usage, weeding practices, field preparation, seeding rate, and sowing techniques (Cooper et al., 2009). For example, the impoverished women farming peanuts on undeveloped plots in urban Ouagadougou, Burkina Faso do not use the modern peanut varieties developed by local agronomists—rather, they rely on known and trusted approaches to grow peanuts as quickly and cheaply as possible to sell peanut butter in the market to meet their household budget (Juana et al., 2013). Ag-Approaches can be used to determine if an improved legume introduced to these women farmers will grow well under variable rainfall, high temperature or other weather scenarios, while acknowledging that the woman farmer will not always be able to plant on the idealized planting window. We could also determine if the new legume variety will still perform when the woman farmer loses access to other inputs due to macro considerations such as fuel prices, inflation or drastic changes in the input supply chain, or how it might be affected by changes in labor availability caused by a catastrophic health concern. The woman farmer's decision-making regarding legume choice involves productivity and flexibility simultaneously, among other concerns. If the crop model answers the first well, then investment might help with the second. Models could also show how productivity investments alone without simultaneous health and input investments will doom our woman farmer's cash crop.

6. Conclusion

Coupling agricultural process models with social and demographic models would enable improved exploration of how to transform low-input subsistence agricultural systems to achieve food security without replicating the unsustainable systems seen elsewhere (Schaller, 1993). This transition requires careful attention to the equity and political processes in the affected communities, the scope and potential of policy interventions, and the practices that result in nutrition and health outcomes. A more integrated modeling framework would allow for the use of modeling scenarios to evaluate potential outcomes and identify the unexpected outcomes that might emerge from biophysical or policy interventions.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://doi.org/10.6084/m9.figshare.19763044.v1.

Author contributions

MB, KG, ME, AC, IC, and JN conceptualized and wrote the paper. AC and IC conceived and designed the analysis and collected the data. AC, IC, and ME performed the analysis. All authors contributed to the article and approved the submitted version.

Funding

This study was supported by the Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) at Kansas State University through funding United States Agency for International Development (USAID) under the Cooperative Agreement (Grant number AID-OAA-L-14-00006).

Acknowledgments

Contribution number 23-160-J from the Kansas Agricultural Experiment Station.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1039962/full#supplementary-material

References

Adegbeye, M. J., Ravi Kanth Reddy, P., Obaisi, A. I., Elghandour, M. M. M. Y., Oyebamiji, K. J., Salem, A. Z. M., et al. (2020). Sustainable agriculture options for production, greenhouse gasses and pollution alleviation, and nutrient recycling in emerging and transitional nations - An overview. *J. Clean. Prod.* 242, 118319. doi: 10.1016/j.jclepro.2019.118319

Ban, N. C., Mills, M., Tam, J., Hicks, C. C., Klain, S., Stoeckl, N., et al. (2013). A social-ecological approach to conservation planning: embedding social considerations. *Front. Ecol. Environ.* 11, 194–202. doi: 10.1890/110205

Bhatta, G. D., and Aggarwal, P. K. (2016). Coping with weather adversity and adaptation to climatic variability: a cross-country study of smallholder farmers in South Asia. *Clim. Dev.* 8, 145–157. doi: 10.1080/17565529.2015.1016883

Brown, M. E., Escobar, V., Younis, F. M., Carlo, E. S., McGroddy, M. E., Arias, S. D., et al. (2022). Scientist-stakeholder relationships drive carbon data product transfer effectiveness within NASA program. *Environ. Res. Lett.* 17, 095004. doi: 10.1088/1748-9326/ac87bf

Brown, M. E., Grace, K., Shively, G., Johnson, K., and Carroll, M. (2014). Using satellite remote sensing and household survey data to assess human health and nutrition response to environmental change. *Popul. Environ.* 36, 48–72. doi: 10.1007/s11111-013-0201-0

Ceballos, F., Kannan, S., and Kramer, B. (2020). Impacts of a national lockdown on smallholder farmers' income and food security: Empirical evidence from two states in India. *World Dev.* 136, 105069. doi: 10.1016/j.worlddev.2020.105069

Cooper, M. W., Brown, M. E., Hochrainer-Stigler, S., Pflug, G., McCallum, I., Fritz, S., et al. (2019). Mapping the effects of drought on child stunting. *Proc. Natl. Acad. Sci. U. S. A.* 116, 17219–17224. doi: 10.1073/pnas.1905228116

Cooper, P., Rao, K. P. C., Singh, P., Dimes, J., Traore, P. C. S., Rao, K., et al. (2009). Farming with current and future climate risk: advancing a Hypothesis of Hope'for rainfed agriculture in the semi-arid tropics. *J. SAT Agric. Res.* 7, 1–19.

Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., et al. (2018). Pursuing sustainable productivity with millions of smallholder farmers. *Nature* 555, 363–366. doi: 10.1038/nature25785

Di Prima, S., Wright, E. P., Sharma, I. K., Syurina, E., and Broerse, J. E. W. (2022). Implementation and scale-up of nutrition-sensitive agriculture in low- and middle-income countries: a systematic review of what works, what doesn't work and why. *Global Food Security* 32, 100595. doi: 10.1016/j.gfs.2021.100595

Fanzo, J., Arabi, B., and Haddad, L. (2016). *Nutrition and Food Systems. High Level Panel of Experts on Food Security and Nutrition (HLPE)*. Available online at: https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/PT_Nutrition/Docs/HLPE_Nutrition_Project-Team_9_May_2016.pdf (accessed April 26, 2022).

Firbank, L. G. (2012). Commentary: pathways to global sustainable agriculture. *Int. J. Agric. Sustainability* 10, 1–4. doi: 10.1080/14735903.2012.621747

Fountas, S., Wulfsohn, D., Blackmore, B. S., Jacobsen, H. L., and Pedersen, S. M. (2006). A model of decision-making and information flows for information-intensive agriculture. *Agric. Syst.* 87, 192–210. doi: 10.1016/j.agsy.2004.12.003

Garrett, R. D., Gardner, T. A., Morello, T. F., Marchand, S., Barlow, J., de Blas, D. E., et al. (2017). Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. *Ecol. Soc.* 22, 220327. doi: 10.5751/ES-09364-220327

Grace, K. (2017). Considering climate in studies of fertility and reproductive health in poor countries. *Nat. Clim. Chang.* 7, 479–485. doi: 10.1038/nclimate3318

Grace, K., Billingsley, S., and Van Riper, D. (2020). Building an interdisciplinary framework to advance conceptual and technical aspects of population-environment research focused on women's and children's health. *Soc. Sci. Med.* 250, 112857. doi: 10.1016/j.socscimed.2020.112857

Grafton, R. Q., Williams, J., and Jiang, Q. (2015). Food and water gaps to 2050: preliminary results from the global food and water system (GFWS) platform. *Food Security* 7, 209–220. doi: 10.1007/s12571-015-0439-8

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., et al. (2017). Natural climate solutions. *Proc. Natl. Acad. Sci. U. S. A.* 114, 11645–11650. doi: 10.1073/pnas.1710465114

Hansen, J., List, G., Downs, S., Carr, E. R., Diro, R., Baethgen, W., et al. (2022). Impact pathways from climate services to SDG2 ("zero hunger"): A synthesis of evidence. *Clim. Risk Manag.* 35, 100399. doi: 10.1016/j.crm.2022.100399

Hansen, J. W., Baethgen, W. E., Osgood, D. E., Ceccato, P. N., and Ngugi, R. K. (2007). *Innovations in Climate Risk Management: Protecting and Building Rural Livelihoods in a Variable and Changing Climate*. Patancheru: SAT eJournal, ICRISAT.

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B. L., Doelman, J. C., et al. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Chang.* 8, 699–703. doi: 10.1038/s41558-018-0230-x

Hirsch, P. D., Adams, W. M., Brosius, J. P., Zia, A., Bariola, N., and Dammert, J. L. (2011). Acknowledging conservation trade-offs and embracing complexity. *Conserv. Biol.* 25, 259–264. doi: 10.1111/j.1523-1739.2010.01608.x

Hoffmann, H., Zhao, G., van Bussel, L. G. J., Enders, A., Specka, X., Sosa, C., et al. (2015). Variability of effects of spatial climate data aggregation on regional yield simulation by crop models. *Clim. Res.* 65, 53–69. doi: 10.3354/cr01326

Holzworth, D., Huth, N. I., Fainges, J., Brown, H., Zurcher, E., Cichota, R., et al. (2018). APSIM next generation: overcoming challenges in modernising a farming systems model. *Environ. Model. Software* 103, 43–51. doi: 10.1016/j.envsoft.2018.02.002

Hoogenboom, G., Porter, C. H., Boote, K. J., Shelia, V., Wilkens, P. W., Singh, U., et al. (2019). "The DSSAT crop modeling ecosystem," in *Advances in Crop Modeling for a Sustainable Agriculture*, eds K. J. Boote (Cambridge: Burleigh Dodds Science Publishing), 173–216.

Horbach, J., Rammer, C., and Rennings, K. (2012). Determinants of eco-innovations by type of environmental impact—The role of regulatory push/pull, technology push and market pull. *Ecol. Econ.* 78, 112–122. doi: 10.1016/j.ecolecon.2012.04.005

Hunter, L. M., Koning, S., Fussell, E., King, B., Rishworth, A., Merdjanoff, A., et al. (2021). Scales and sensitivities in climate vulnerability, displacement, and health. *Popul. Environ.* 43, 61–81. doi: 10.1007/s11111-021-00377-7

Jain, M. (2020). The benefits and pitfalls of using satellite data for causal inference. *Rev. Environ. Econ. Policy* 14, 157–169. doi: 10.1093/reep/rez023

Juana, J., Kahaka, Z., and Okurut, F. (2013). Farmers' perceptions and adaptations to climate change in Sub-Sahara Africa: a synthesis of empirical studies and implications for public policy in African Agriculture. *J. Agric. Sci.* 5, 121. doi: 10.5539/jas.v5n4p121

Keating, B. A., Carberry, P. C., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., et al. (2003). An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 18, 267–288. doi: 10.1016/S1161-0301(02)00108-9

Lemos, M. C., and Morehouse, B. J. (2005). The co-production of science and policy in integrated climate assessments. *Glob. Environ. Change* 15, 57–68. doi: 10.1016/j.gloenvcha.2004.09.004

Lobell, D., and Gourdji, S. (2012). The influence of climate change on global crop productivity. *Plant Physiol.* 112, 208298. doi: 10.1104/pp.112.208298

Loos, J., Abson, D. J., Chappell, M. J., Hanspach, J., Mikulcak, F., Tichit, M., et al. (2014). Putting meaning back into "sustainable intensification." *Front. Ecol. Environ.* 12, 130157. doi: 10.1890/130157

Meemken, E.-M., Sellare, J., Kouame, C. N., and Qaim, M. (2019). Effects of Fairtrade on the livelihoods of poor rural workers. *Nat. Sustain.* 2, 635–642. doi: 10.1038/s41893-019-0311-5

Moberg, E., Karlsson Potter, H., Wood, A., Hansson, P.-A., and Röös, E. (2020). Benchmarking the Swedish diet relative to global and national environmental targets—identification of indicator limitations and data gaps. *Sustain. Sci. Pract. Policy* 12, 1407. doi: 10.3390/su12041407

Musumba, M., Grabowski, P., Palm, C., and Snapp, S. (2017). *Guide for the Sustainable Intensification Assessment Framework*. Patancheru: SAT eJournal, ICRISAT.

Nagendra, H., Bai, X., Brondizio, E. S., and Lwasa, S. (2018). The urban south and the predicament of global sustainability. *Nat. Sustain.* 1, 341–349. doi: 10.1038/s41893-018-0101-5

Osgood, D., Powell, B., Diro, R., Farah, C., Enenkel, M., Brown, M., et al. (2018). Farmer perception, recollection, and remote sensing in weather index insurance: an Ethiopia case study. *Remote Sensing* 10, 1887. doi: 10.3390/rs10121887

Oyinbo, O., Chamberlin, J., and Maertens, M. (2020). Design of digital agricultural extension tools: perspectives from extension agents in Nigeria. *J. Agric. Econ.* 71, 798–815. doi: 10.1111/1477-9552.12371

Peng, B., Guan, K., Tang, J., Ainsworth, E. A., Asseng, S., Bernacchi, C. J., et al. (2020). Towards a multiscale crop modelling framework for climate change adaptation assessment. *Nat. Plants* 6, 338–348. doi: 10.1038/s41477-020-0625-3

Phalkey, R. K., Aranda-Jan, C., Marx, S., Höfle, B., and Sauerborn, R. (2015). Systematic review of current efforts to quantify the impacts of climate change on undernutrition. *Proc. Natl. Acad. Sci.* 112, E4522–E4529. doi: 10.1073/pnas.1409769112

Pilling, D., Bélanger, J., and Hoffmann, I. (2020). Declining biodiversity for food and agriculture needs urgent global action. *Nat. Food* 1, 144–147. doi: 10.1038/s43016-020-0040-y

Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., et al. (2018). Global assessment of agricultural system redesign for sustainable intensification. *Nat. Sustain.* 1, 441–446. doi: 10.1038/s41893-018-0114-0

Pretty, J. N. (1997). The sustainable intensification of agriculture. *Nat. Resour. Forum* 21, 247–256. doi: 10.1111/j.1477-8947.1997.tb00699.x

Randell, H., Grace, K., and Bakhtsiyarava, M. (2021). Climatic conditions and infant care: implications for child nutrition in rural Ethiopia. *Popul. Environ.* 42, 524–552. doi: 10.1007/s11111-020-00373-3

Randell, H., and Gray, C. (2019). Climate change and educational attainment in the global tropics. *Proc. Natl. Acad. Sci.* 116, 8840–8845. doi: 10.1073/pnas.1817480116

Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., and Chookolingo, B. (2018). How much of the world's food do smallholders produce? *Global Food Security* 17, 64–72. doi: 10.1016/j.gfs.2018.05.002

Ritzema, R. S., Frelat, R., Douxchamps, S., Silvestri, S., Rufino, M. C., Herrero, M., et al. (2017). Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from East and West Africa. *Food Security* 9, 115–131. doi: 10.1007/s12571-016-0638-y

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., et al. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* 46, 4–17. doi: 10.1007/s13280-016-0793-6

Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., et al. (2020). Five ways to ensure that models serve society: a manifesto. *Nature* 582, 482–484. doi: 10.1038/d41586-020-01812-9

Schaller, N. (1993). The concept of agricultural sustainability. *Agric. Ecosyst. Environ.* 46, 89–97. doi: 10.1016/0167-8809(93)90016-I

Sellers, S., and Gray, C. (2019). Climate shocks constrain human fertility in Indonesia. *World Dev.* 117, 357–369. doi: 10.1016/j.worlddev.2019.02.003

Shively, G., Sununtnasuk, C., and Brown, M. (2015). Environmental variability and child growth in Nepal. *Health Place* 35, 37–51. doi: 10.1016/j.healthplace.2015.06.008

Shively, G. E. (2017). Infrastructure mitigates the sensitivity of child growth to local agriculture and rainfall in Nepal and Uganda. *Proc. Natl. Acad. Sci. U. S. A.* 114, 903–908. doi: 10.1073/pnas.1524482114

Sibhatu, K. T., and Qaim, M. (2017). Rural food security, subsistence agriculture, and seasonality. *PLoS ONE* 12, e0186406. doi: 10.1371/journal.pone.0186406

Siddique, K. H. M., Johansen, C., Turner, N. C., Jeuffroy, M.-H., Hashem, A., Sakar, D., et al. (2012). Innovations in agronomy for food legumes. A review. *Agron. Sustain. Dev.* 32, 45–64. doi: 10.1007/s13593-011-0021-5

Spiegel, A., and Satterthwaite, D. (2013). *The R4 Rural Resilience Initiative—Protecting Livelihoods in a Changing Climate*. The Geneva Reports 65. Available online at: https://web.actuaries.ie/sites/default/files/erm-resources/ga_2013_geneva_report_7.pdf#page=73 (accessed June 6, 2022).

Stevenson, J., Vanlauwe, B., Macours, K., Johnson, N., Krishnan, L., Place, F., et al. (2019). Farmer adoption of plot- and farm-level natural resource management practices: between rhetoric and reality. *Global Food Security* 20, 101–104. doi: 10.1016/j.gfs.2019.01.003

Stewart, Z. P., Middendorf, B. J., Musumba, M., Grabowski, P., Palm, C., Snapp, S., et al. (2018). *sitoolkit.com*©. Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification, Kansas State University, Manhattan, KS, United States.

Valin, H., Sands, R. D., Van der Mensbrugghe, D., Nelson, G. C., Ahammad, H., Blanc, E., et al. (2014). The future of food demand: understanding differences in global economic models. *Agric. Econ.* 45, 51–67. doi: 10.1111/agec.12089

Velten, S., Leventon, J., Jager, N., and Newig, J. (2015). What is sustainable agriculture? A systematic review. *Sustain. Sci. Pract. Policy* 7, 7833–7865. doi: 10.3390/su7067833

Yaro, J. A. (2006). Is deagrarianisation real? A study of livelihood activities in rural northern Ghana. *J. Mod. Afr. Stud.* 44, 125–156. doi: 10.1017/S0022278X05001448

Zurek, M., Keenlyside, P., and Brandt, K. (2016). *Intensifying Agricultural Production Sustainably: A Framework for Analysis and Decision Support*. Washington, DC: Intl Food Policy Res Inst; Climate Focus.

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 06 March 2023
DOI 10.3389/fsufs.2023.1051356

Check for updates

OPEN ACCESS

EDITED BY
Ruben G. Echeverria,
Bill and Melinda Gates Foundation,
United States

REVIEWED BY
Pablo Pérez-Akaki,
Monterrey Institute of Technology and Higher Education (ITESM), Mexico
Carl Pray,
Rutgers, The State University of New Jersey,
United States

*CORRESPONDENCE
Gert-Jan Stads
g.stads@cgiar.org

SPECIALTY SECTION
This article was submitted to
Land, Livelihoods and Food Security,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 22 September 2022
ACCEPTED 10 February 2023
PUBLISHED 06 March 2023

CITATION
Nin-Pratt A and Stads G-J (2023) Innovation capacity, food system development, and the size of the agricultural research system.
Front. Sustain. Food Syst. 7:1051356.
doi: 10.3389/fsufs.2023.1051356

Innovation capacity, food system development, and the size of the agricultural research system

Alejandro Nin-Pratt and Gert-Jan Stads*

Environment and Production Technology Division, International Food Policy Research Institute, Washington, DC, United States

Introduction: This article contributes to a better understanding of the context in which agricultural R&D investment takes place in low- and middle-income countries, and how innovation capacity, the development of the food system, and the size of the research system affect R&D investment.

Methods: A three-step methodology is proposed where the first step consists of creating an index of the development of a food system using indicators of the technological transformation of the food supply chain and the changes in diets on the demand side. The second step involves developing a measure of innovation capacity at the country level, while the final step consists of systematic comparisons of countries with large and small agricultural research systems to find the relationship between the size of a country's research system, the level of development of its food system, and its overall capacity to innovate.

Results: The results reveal that there is a high and positive correlation between innovation capacity and the development of the food system and a negative correlation between these two indicators and the size of the agricultural research system in low- and middle-income countries. The lower overall quality and level of development of the education and scientific research systems in countries with small agricultural research systems are important factors contributing to reduced innovation capacity. In addition, countries with small agricultural research systems are challenged with a comparatively poor innovation environment, poor market development, a weak private sector, a lack of competition in domestic markets, and a largely rural population with poor links to markets.

Discussion: The results of the analysis stress the need to increase the efficiency and productivity of agricultural research by implementing policies that get the most out of available resources while minimizing the negative effect of small-scale research operations. Increased coordination and integration of agricultural research at the regional and global level can help avoid duplication, enhance the efficiency of small-scale organizations, and make research more cost-effective and impactful.

KEYWORDS

agriculture, food system, innovation, research system, R&D investment

1. Introduction

As the world's population moves toward 10 billion by 2050, unprecedented increases in global food production—of at least 60% over 2007 levels—will be needed to meet growing demand. Innovation is essential to address challenges associated with population growth and those caused by increased pressure on natural resources and climate change. Innovation will be needed in agricultural technologies to increase and diversify production in ways that make more efficient use of resources, but it will also be needed in the infrastructure, institutions, and services that support food systems to make them more inclusive, resilient, and sustainable (Stads et al., 2022).

There is considerable evidence that investing in agricultural research is a highly effective pathway for both reducing poverty and hunger and addressing climate change impacts on food systems (Rosegrant et al., 2017; Mason-D'Croz et al., 2019; Agricultural Science and Technology Indicators, 2022). Regardless of the mode of investments, timeframe, 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, and farm subsidies, or with investments in other rural areas, such as health, education, and roads (Diaz-Bonilla et al., 2014; Mogues, 2015).

Given the widespread evidence of the positive impact of agricultural R&D investment on agricultural productivity and poverty reduction, it is no surprise that global agricultural research spending grew by 50% (in inflation-adjusted terms) during 2000–2016. This global growth, however, was mostly driven by China and other large middle-income countries, while growth in high-income countries (HICs) has largely stalled (Beintema et al., 2020). Coinciding with the observed fast growth in R&D spending in low-and middle-income countries (LMICs), the global gap in agricultural research investment—that is actual agricultural research investment as a percentage of attainable investment levels—dropped from 45% in 1996 to 39% in 2016 (see Nin-Pratt, 2021 for more information on investment gaps).

Accelerated growth in agricultural R&D investment in LMICs could be construed as very good news given the vast amount of literature going back decades showing that the returns to agricultural R&D investment average around 40–60% (Alston et al., 2000; Evenson, 2001), and that there has been substantial underinvestment in public agricultural R&D (Roseboom, 2003). Yet, a closer look at R&D investment data reveals that the investment gap in LMICs other than China and India as a group has widened since 2008 after contracting significantly in the early 2000's (Nin-Pratt, 2021).

A recent study by Rao et al. (2019), which used a newly updated and expanded global database of estimated returns to agricultural R&D and a robust statistical methodology, finds that today's returns to agricultural R&D investments are as high as ever. Yet, most LMICs continue to underinvest. James et al. (2008) point to three distinct features of LMICs that can help explain the underinvestment challenge: incomplete markets, appropriability problems, and price distortions. First, LMICs face a comparatively high incidence of incomplete markets, resulting from high transaction costs and inadequate property rights, which in turn may be attributable to inadequate infrastructure and defective institutions. These are likely to reduce adoption rates of new inventions, decreasing the expected returns, and increasing the risk of R&D investments. Second, appropriability problems are more pronounced for the types of technological innovations best suited to much of LMIC agriculture, such as improved crop varieties and farm management practices—innovations that have been comparatively neglected by the private sector. Third, in many developing countries, poor policies and distorted prices have diminished incentives and opportunities for farmers to adopt new technologies.

James et al. (2008) also point to additional features that contribute to underinvestment in the public sector. Budget constraints due to low government revenues together with underinvestment in several other essential public goods, including transportation and communications infrastructure, schools, and hospitals, can result in high social rates of return on these investments and high opportunity costs for investment in agricultural research. Adding to this, agriculture in less developed LMICs represents a much greater share of the total economic activity and per capita incomes are much lower relative to higher-income countries. Under such circumstances, investment in public agricultural research can impose a much higher cost on individual citizens, especially when this burden is felt now and the payoff may take years or decades to come, thereby diminishing the political appeal of supporting agricultural R&D. Finally, one of the factors determining the extent of underinvestment in agricultural R&D, which is particularly relevant for this study, is that of economies of scale in knowledge accumulation and dissemination. In most cases, LMICs attempting to conduct most of their own research may be too small to achieve an efficient scale in many, if any, of their R&D priority areas. If technological spillovers are available and accessible, it might not make sense for small, poor, agrarian nations to spend their scarce intellectual and other capital resources on agricultural science.

This article revisits the agricultural R&D underinvestment problem in LMICs with the aim of contributing to a better understanding of the context in which public R&D investment takes place, and how innovation capacity, the development of the food system, and the size of the research system affect R&D investment. This is achieved by using the analytical framework of the food system developed by Reardon et al. (2019) together with elements of the agricultural information system (AIS) approach by (Spielman and Birner, 2008). The hypothesis motivating the analysis is that research systems are endogenous to the development process. In other words, countries with more developed food systems are better positioned to get the most out of their agricultural R&D investment as they have more developed value chains, better integrated national output and input markets, and better infrastructure. This implies a positive correlation between the development of the food system and a country's capacity to innovate, which is a function of several factors, including the quality of human capital and research capacity, the innovation environment, innovation policies, and institutions. If this is the case, LMICs face the chicken-and-egg dilemma of not being able to increase agricultural research efficiently to promote innovation and development, precisely because they are underdeveloped and lack the capacity to innovate. On the other hand, it is not clear a priori why R&D investment is growing faster in LMICs with large agricultural R&D systems. Is the better investment performance of large LMIC economies explained mostly by economies of scale in research, or are there also important differences in innovation capacity and food system development in these countries?

To answer these questions, we look at the evolution of global agricultural R&D investment, breaking down the analysis by countries' income levels and the size of their R&D systems. This is followed by the conceptual framework, methodology, and data used to build indices of food system development and of innovation capacity. The subsequent section presents the results of an analysis of the productivity, costs, and scale of agricultural research systems in the context of food system development and agricultural innovation capacity, while the concluding section discusses the main findings and suggests policy implications.

2. Long-term trends in agricultural R&D investment

In inflation-adjusted terms, global public agricultural research investment doubled between 1981 and 2016 (Figure 1). While HICs still accounted for the bulk of research spending around the turn of the millennium, rapid increases in spending by large middle-income countries, coupled with stagnating spending growth in HICs, have shifted the global balance. By 2016, LMICs accounted for nearly 60% of global agricultural research spending. China, India, and Brazil alone accounted for more than half of LMIC spending, while sub-Saharan Africa's (SSA's) share in global public agricultural R&D spending has stagnated at about 5% (Agricultural Science and Technology Indicators, 2022). Private sector involvement in agricultural research also shifted the balance in investment. Private spending tripled from $5.1 to $15.6 billion globally between 1990 and 2014, outpacing growth in public spending. Though most private R&D expenditures originate in HICs, more than a quarter of these expenditures directly target commodities or research areas relevant to LMIC farmers (Fuglie, 2016).

Figure 2 groups the 98 countries included in the analysis based on the size of their research system (measured by average annual investment in 2011 PPP dollars at the beginning and end of the 1996–2016 period). During 1996–2000 (Figure 2A), the seven countries investing more than 1,000 million PPP dollars (in 2011 constant prices) were Germany, Indonesia, France, India, Brazil, Japan, and the United States. The group of countries investing between 400 and 1,000 million PPP dollars during 1996–2000 included seven HICs as well as 5 LMICs, namely: Egypt, Argentina, Mexico, Malaysia, and China. The group investing between 100 and 400 million PPP dollars includes Kenya, Morocco, Nigeria, and South Africa in SSA, Bangladesh, Philippines, Pakistan, and Thailand in the Asia-Pacific region, and Chile and Colombia in the Latin America and Caribbean (LAC) region. The largest research systems among countries investing 100 million PPP dollars or less include Vietnam, Côte d'Ivoire, Algeria, Ghana, and Sri Lanka. The average size of investment for the 98 countries combined was more than 60 million PPP dollars during 1996–2000.

Figure 2B shows the distribution of countries by their level of R&D investment during 2011–2016. Sixty-one of the 98 countries are still in the same investment group as they were during 1996–2000; 28 countries moved to a higher investment group, while nine countries moved to a lower investment group. The main difference can be observed in the group investing <10 million PPP dollars. The number of countries in this group decreased from 13 to 8. Details of the distribution of countries by R&D spending levels at the beginning and end of the period summarized in Figure 2 can be found in the Supplementary material to this article.

To study the differences in investment and performance between countries with large and small agricultural research systems, countries' agricultural research systems were classified as small, medium, or large, based on average R&D investment levels during 1996–2000, the beginning of the period of analysis. R&D investment and other indicators for the period 2000–2016 from the groups of small, medium, and large countries are then used to compare investment performance and other characteristics of the three groups.[1] The group of countries with large agricultural research systems (Large) includes those LMICs in the highest 20% of the distribution shown in Figure 2A, i.e., those with average annual R&D investment of more than 400 million PPP dollars during 1996–2000. The LMICs in this group include China, Brazil, India, Argentina, Indonesia, Mexico, Egypt, and Malaysia. On the other extreme, countries spending <100 million PPP dollars in agricultural R&D during 1996–2000 are included in the group of countries with small research systems (Small). This group is very heterogeneous, with annual investments ranging from 1 to 100 million PPP dollars. Between these two groups, countries with medium-size research systems (Medium), are those with an average annual agricultural R&D investment ranging from 100 to 400 million PPP dollars.[2]

As Figure 3 shows, annual investment levels by large agricultural research systems are considerably higher than those by medium-sized and small systems, both in absolute and relative per-capita terms. Moreover, large systems' long-term growth in agricultural research investment has far exceeded investment growth in other LMICs as well as HICs. Large LMICs have also been the main driver behind global growth in agricultural R&D investment. China alone was responsible for about half of this increase in global investment.

Increasing the productivity of agricultural production—that is, getting more output from the same amount of resources—is critical for improving food security. TFP is an indicator of how efficiently agricultural land, labor, capital, and other inputs (seed, fertilizer, and so on) are used to produce a

1 For example, to look at differences in the number of publications in agricultural and biological science by group, the groups of countries with large, medium, and small research systems are defined by the average R&D investment of each country at the beginning of the period (1996–2000). The number of publications of these three groups presented in the results represents articles published between 2000 and 2016 by countries in each group.

2 The purpose of defining a Medium group is to clearly separate the two extreme groups: Large and Small. A different group classification could be to include countries above median R&D investment in the Medium group. Nonetheless, the conclusions of the analysis would remain the same. If the Medium group is merged with the Large group, differences between Small and Large would still be large and significant. If the Medium group is expanded to include some of the larger countries from the small group, differences between Small and Large would increase.

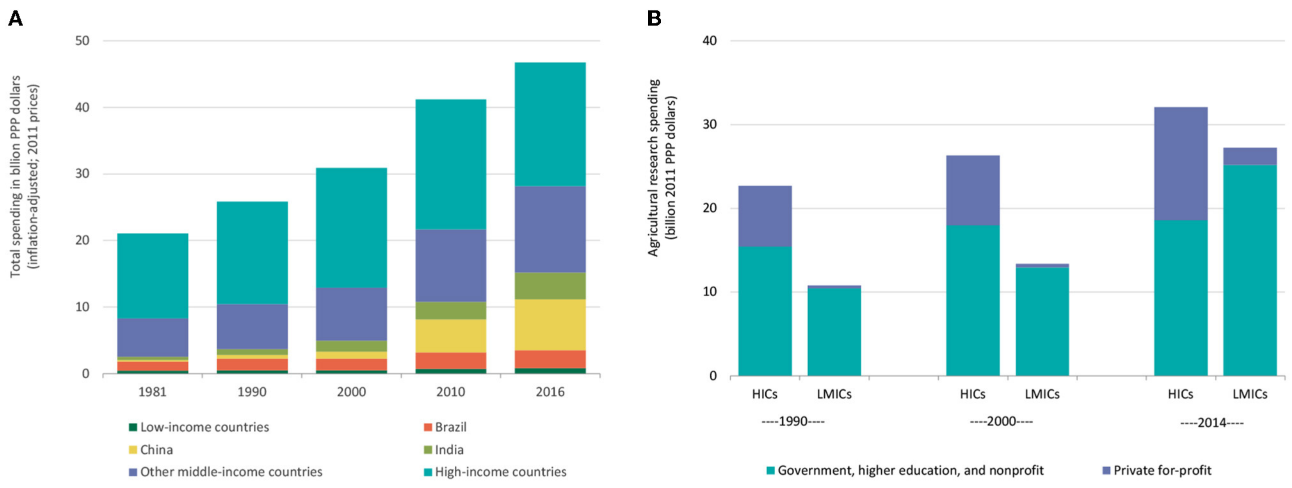


FIGURE 1
Long-term trends in agricultural research spending. **(A)** Public spending by income group, 1981–2016. **(B)** Public and private spending by income group, 1990–2014. Sources: Fuglie (2016) and Agricultural Science and Technology Indicators (2022).

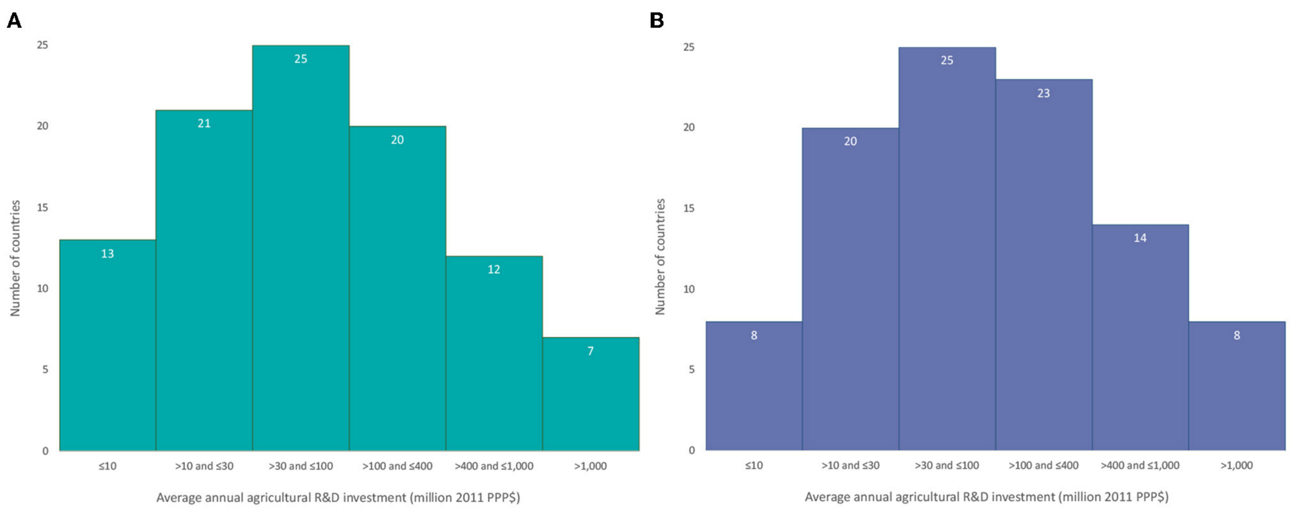


FIGURE 2
Size distribution of national agricultural research systems based on average annual investment levels. **(A)** 1996–2000. **(B)** 2011–2016. Source: Elaborated by authors based on Agricultural Science and Technology Indicators (2022).

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 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, are major drivers as well. During 1996–2016, global TFP increased steadily (United States Department of Agriculture, Economic Research Service, 2022). Large LMICs, which were the main drivers of global growth in agricultural R&D spending, were also the main drivers of global growth in TFP. Over this period, TFP growth in large LMICs was nearly twice as high as in smaller LMICs and HICs (Figure 4).

Table 1 reveals that there are important structural differences between LMICs with large, medium, and small national agricultural research systems. With almost 1 billion people living in countries with small agricultural research systems, these countries account for 15% of the global population and 12% of global agricultural GDP (AgGDP). Yet, they generate only 5% of global GDP, and their average GDP per capita is about half of that in Large countries. Agricultural R&D investment by LMICs averaged around 22 billion PPP dollars during 2013–2016, equivalent to 56% of global agricultural R&D spending.

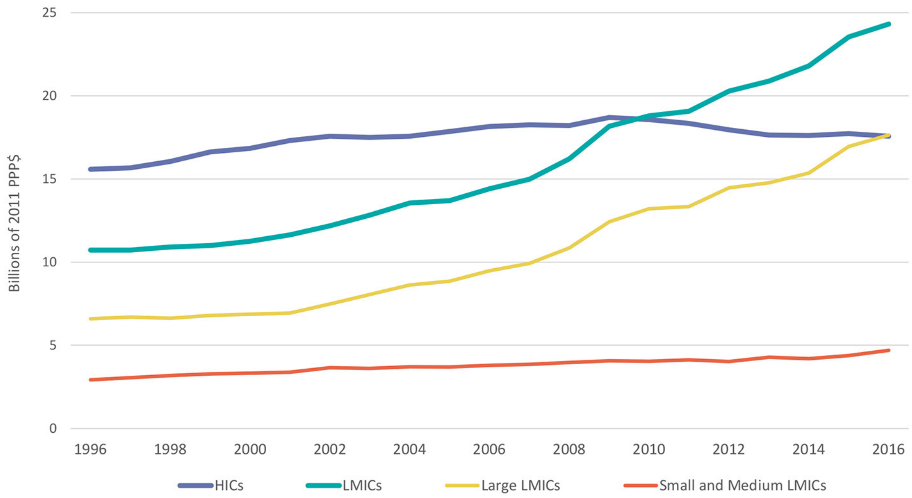


FIGURE 3
Trends in public agricultural R&D investment in HICs and LMICs grouped by the size of their research system, 1996–2016. Sources: Elaborated by authors based on Agricultural Science and Technology Indicators (2022) and United States Department of Agriculture, Economic Research Service (2022). The size of the national agricultural research system is determined based on average annual agricultural R&D investment (in 2011 PPP$) for the 1996–2000 period. Large: >400 million PPP$; Medium: 100–400 million PPP$; and Small: <100 million PPP$.

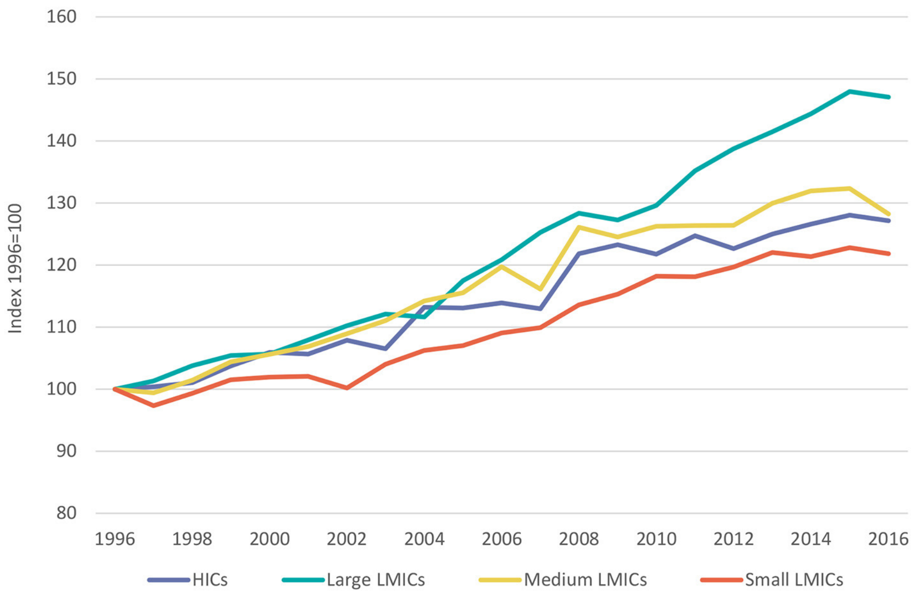


FIGURE 4
TFP growth in HICs and LMICs with large, medium, and small agricultural research system, 1996–2016. Sources: Elaborated by authors based on Agricultural Science and Technology Indicators (2022) and United States Department of Agriculture, Economic Research Service (2022). The size of the national agricultural research system is determined based on average annual agricultural R&D investment (in 2011 PPP$) for the 1996–2000 period. Large: >400 million PPP$; Medium: 100–400 million PPP$; and Small: <100 million PPP$.

However, countries with small research systems contributed only 6% of R&D spending, similar to their contribution to global GDP.

These figures provide a simple and intuitive explanation of why the share of agricultural R&D investment in AgGDP is not a good measure of a country's effort in R&D investment. Table 1 shows that this share in HICs is 2.8%, much higher than the 0.4% recorded in LMICs. However, if GDP is used instead of AgGDP, the difference in R&D investment "intensity" between HICs and LMICs disappears. In fact, the share of agricultural R&D investment in GDP is actually higher in LMICs (0.047%) than in HICs (0.040%), with Small countries showing the highest share (0.052%) among the four groups of countries. In other words, Small countries are investing more in agricultural R&D relative to the size of their economy than HICs. These country differences are, perhaps, not too surprising. With a much smaller share of agriculture in GDP and higher GDP per capita, HICs are in a position to invest more relative to AgGDP than LMICs, and there

TABLE 1 Macroeconomic and agricultural R&D investment indicators for HICs and LMICs grouped by the size of the research system.

		Low- and middle-income			
	HIC	Total LMIC	Large	Medium	Small
Totals					
Population (million)	1,049	5,344	3,436	972	936
Share of total global population (%)	16	84	54	15	15
GDP (billions 2011 PPP$)	43,045	46,729	34,559	7,704	4,466
Share of total global GDP (%)	48	52	38	9	5
AgGDP (billions 2011 PPP$)	612	5,038	3,483	900	655
Share of total global AgGDP	11	89	62	16	12
Share of agriculture in GDP (%)	1.4	10.8	10.1	11.7	14.7
GDP per capita (2011 dollars)	41,033	8,744	10,059	7,923	4,771
Public agricultural R&D spending (million 2011 dollars), 2013–2016 averages	17,160	22,022	15,838	3,881	2,302
Share of total global agricultural R&D investment	43.8	56.2	40.4	9.9	5.9
Public agricultural R&D spending/AgGDP (%)	2.8	0.4	0.5	0.4	0.4
Public agricultural R&D spending/GDP (%)	0.040	0.047	0.046	0.050	0.052
Public agricultural R&D spending, annual growth rate 1991–2016 (%)	0.6	4.5	5.5	2.6	2.5
Country averages					
Number of countries	26	72	8	11	53
Population (million)	40	74	429	88	18
GDP (billions 2011 PPP$)	1,656	649	4,320	700	84
AgGDP (billions 2011 PPP$)	24	70	435	82	12
Public agricultural R&D spending (million 2011 dollars), 2013–2016 averages	660	306	1,980	353	43

Sources: Elaborated by authors based on Agricultural Science and Technology Indicators (2022) and World Bank (2022).
Size of the national agricultural research system is defined based on average annual R&D investment (in 2011 PPP$) for the period 1996–2000. Large: >400 million PPP$; Medium: ≥100 and ≤400 million PPP$; and Small: ≤100 million PPP$.

are a number of political economy factors explaining the reasons for this, which will be discussed later.

The bottom rows in Table 1 summarize the important size differences that exist across country groups in terms of population, GDP, AgGDP, and agricultural R&D spending. For example, the average Small country spends more than eight times less in agricultural R&D than the average Medium country and nearly fifty times less than the average Large country.

3. Conceptual framework

New developments in the dialogue about the transformation of the food system and how knowledge is transformed into innovations have clear implications for the analysis of public agricultural R&D investment and the factors behind underinvestment in LMICs. This complexity seems to be at odds with a mechanistic view of policy research and investment that assumes that the production of new knowledge by the National Agricultural Research System (NARS) is in practical terms, exogenous to the economic and social conditions of the country and the structural variables that determine them. This might well be the assumption behind the across-the-board recommendation to governments in LMICs to increase investment in agricultural research without distinction of the country's level of development, research capacity, research institutions, and opportunity costs of alternative investments. The point here is not to deny the importance of agricultural R&D investment but rather approach research as part of a knowledge value chain in the food system, and as such, subject to the same complexities and constraints as the other value chains in the food system. For this reason, there is a need to refine the conceptual and analytical tools to identify how policies and investments can best promote innovative behavior and practices in the agricultural sector.

3.1. The innovation system

Spielman and Birner (2008) argue that the agricultural innovation system (AIS) framework offers an interesting perspective for guiding investment and policy interventions in this area. The World Bank (2006) defines an innovation system as "…a network of organizations, enterprises, and individuals focused on bringing new products, new processes, and new forms of organization into economic use, together with the institutions and policies that affect their behavior and performance." This approach to the analysis of innovations includes not only the science suppliers, but it extends beyond the creation of knowledge to encompass the factors affecting demand for and use of knowledge (World Bank, 2006).

Spielman and Birner (2008) propose a conceptual framework of the AIS that captures its essential elements, the linkages between these elements, and the institutions and policies that constitute the enabling environment for innovation. According to this framework, essential elements of an innovation system include (a) a knowledge and education domain composed of the agricultural research and education systems; (b) a business and enterprise domain that includes the set of value chain actors and activities that both use outputs from the knowledge and education domain and innovate independently; (c) bridging institutions that link the two domains, including extension services, political channels, and stakeholder platforms—that facilitate the transfer of knowledge and information between the domains; and (d) the context conditions that foster or impede innovation, including public policies on innovation and agriculture; and informal institutions that condition how individuals and organizations within each domain act and interact. Influencing factors that are not part of the system include the linkages to other sectors of the economy (manufacturing and services); general science and technology policy; international sources of knowledge and markets; and the political system.

3.2. The food system

According to Reardon et al. (2019), a food system is a cluster of value chains that includes farmers producing agricultural output; inputs that are supplied to farmers and the post-farmgate segments of the system; rural and urban wholesalers; transporters who bring outputs and inputs to markets, to the processing industry, and retailers; and financial services offered to each segment and every chain in the system. The R&D supply chain is closely linked with the other components of the system to deliver technology and product innovations. It comprises the NARS, private players investing in R&D, the International Agricultural Research Centers (IARCs), and universities. A broad set of public assets such as infrastructure, police protection, court systems for contract enforcement, and innovation policies act as the "lubricant" between the different value chains, facilitating linkages within the system, and with other systems in the economy (Reardon et al., 2019).

Urbanization, income growth, and population growth play crucial roles in the structural transformation of food systems. Urbanization fuels the spatial expansion of supply chains as cities need larger catchment areas to feed themselves. At the initial stages of development, supply chains in the food system are mostly local, with most of the value added occurring at the farm level and limited involvement by off-farm players in the supply chain. As the chain grows longer and economies of specialization emerge in the midstream and downstream segments of the chain, the role of post-farmgate segments grows while the farmers' share in the total value added of the chain drops (Reardon et al., 2019).

Longer value chains and the specialization in the chain's downstream segments result in product differentiation and the rise of trade in perishables, triggering institutional changes along the chain. One of these changes is the emergence of quality and safety standards, formulated by supermarket chains, large processors, and fast-food chains to reduce losses in processing, increase shelf life, control quality, and consistency, and assure safety. Governments also institute public food safety regulations for retail and food service (Reardon et al., 2019).

Finance arrangements also evolve as the food system develops. In traditional systems, farmers receive money or input from traders in advance to be paid back with the harvest. As food systems evolve, and competition among traders and farmers increases, off-farm cash sources become more common, as does increased vertical integration in some value chains where contracts are used when food industry firms must rely on small farmers to complete their supply and farmers face market failures for credit and inputs (Reardon et al., 2019).

Increased urbanization and income growth also prompt shifts in diets. As citizens can afford to spend a higher proportion of their budget on non-staple foods, the supply chains of vegetables and fruit, meat and fish, dairy, and edible oils become more sophisticated. Pro-market policies tend to favor these changes as they increase the participation of the private sector (large input firms, processors, supermarkets, and fast-food chains) encouraged by the expanding urban markets. Finally, investments in infrastructure facilitate the development of the food supply chain from rural areas to cities and towns by reducing transaction costs and strengthening linkages between supply chains (Reardon et al., 2019).

With urbanization and rising labor participation in industry and services, labor in agriculture becomes increasingly scarce. The limited supply of labor increases labor costs and the use of capital inputs and investments per worker to enhance labor productivity. Responding to the increased demand for capital inputs, countries increase supply by industrializing production or increasing imports. This drives down the cost of capital inputs. With labor scarcity increasing, technical change and capital intensification among farmers are induced. The use of capital inputs is also powered by research and the production of high-yield crop varieties and improved livestock breeds adapted to local conditions that produce more output per unit of input. As urban demand rises and production specializes, the importance of breeding for traits of quality and the ability to store and process agricultural commodities increases relative to breeding for yield (Reardon et al., 2019).

As with farm technologies, a gradual increase in wages, combined with a decrease in physical capital prices (from local industrialization and imports), induces midstream and downstream capital intensification and upgrading. On the other hand, demand-side factors such as the demand for new products, improved quality, and safety attributes, and greater and more storable volumes also induce technological change. Much of the initial innovation occurred earlier, in HICs, and was transferred and adapted to LMICs. These technological advances include among others, innovations in logistics, processing, freezing, packaging, traceability, inventory, and safety monitoring technologies.

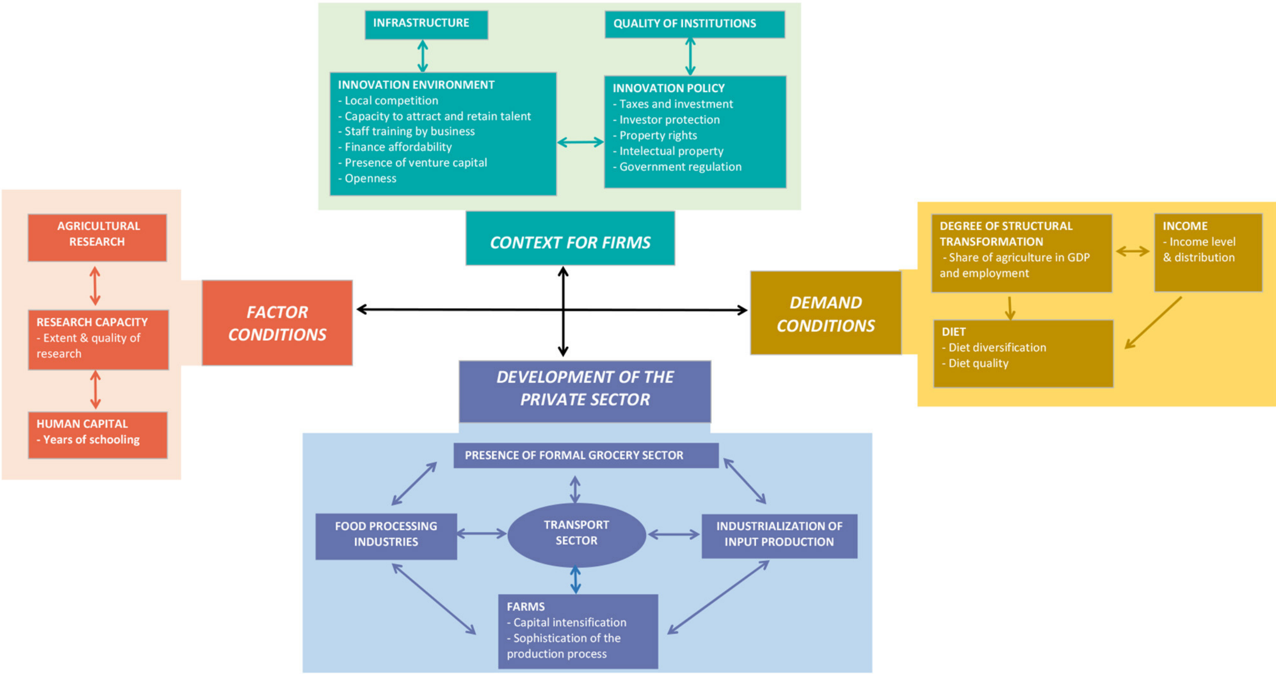


FIGURE 5
The food system and the innovation context. Sources: Elaborated by authors based on Porter and Stern (2001), Spielman and Birner (2008), and Reardon et al. (2019).

3.3. Links between innovation and food systems

Innovation and food systems overlap to a certain extent. This is because several of the factors that contribute to a country's capacity to innovate are precisely the factors that determine the level of development of a food system. Figure 5 attempts to capture this relationship by laying out the different food system components in the form of a Porter Diamond representing a country's environment for innovation (Porter and Stern, 2001). The four vertexes of the diamond display the attributes affecting innovation in the food system as well as its overall competitiveness. The first of these attributes is what Porter calls the factor conditions. The presence of high-quality human capital is one of these factor conditions. It determines the capacity of the agricultural research system, and at the same time, it is the product of the quality and scope of the education system and the development of scientific research in the country.

The second attribute is the development and strength of the private sector, reflected by the firms that take part in the food system directly and those that provide services and inputs to them. Developed output and input markets, the length and breadth of the value chains, the development of industrial clusters, vertical integration, or tighter links between upstream and low-stream segments of the chain indicate a more developed food chain.

The third attribute is food demand, which is associated with income growth, shifts in diets, urbanization, and increased labor participation in industry and services. Food demand acts as a pull factor in the development of the value chain in that it influences the types and quality of products produced. It also has the potential to determine technology changes at the farm level and investment in the off-farm segments of the chain.

Finally, the "environment" in which firms in the private sector operate is the fourth attribute of the diamond. It includes a country's innovation environment, which is the product of the level of local competition, the capacity to attract and retain talent, affordability of credit, the presence of venture capital, and other factors. This environment is shaped and affected by innovation policies, infrastructure (especially in communications and IT), and by the quality of institutions.

3.4. Indices to quantify innovation capacity and food system development

To gain a better understanding of the factors behind public R&D investment, and how innovation capacity and structural country characteristics affect investment at different stages of development of the food system, a three-step methodology is proposed based on the conceptual framework summarized in Figure 5. The first step is the construction of an index that quantifies the development of a food system using indicators that capture the technological transformation of the food supply chain and the changes in diets that act as demand-side pull factors. Two sub-indices measure the technological transformation of the supply side of the food system. The first sub-index is a measure of intensity in the use of capital inputs—irrigation equipment, seeds, fertilizer, insecticides, herbicides, tractors and combines, and sprayers—measured as total capital inputs per worker. The second sub-index quantifies post-farm innovations reflected in the "length" and

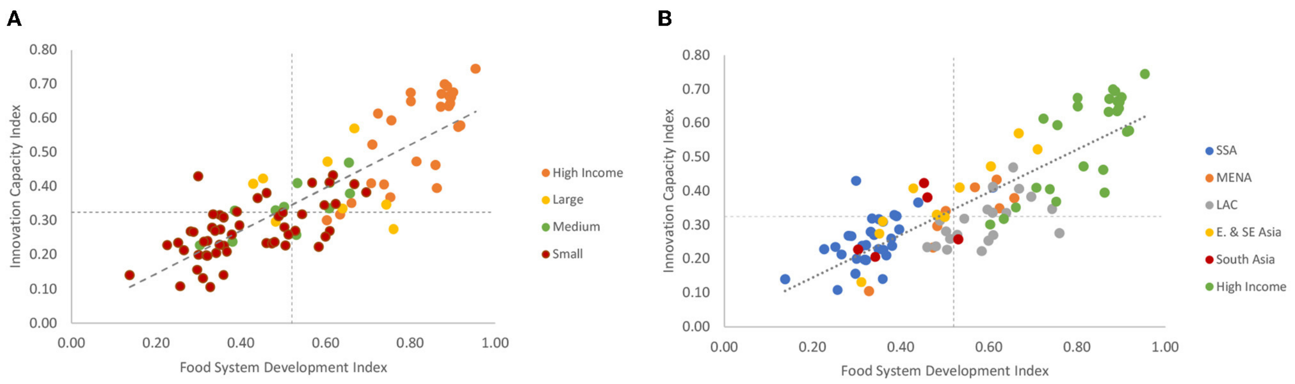


FIGURE 6
Food system development vs. innovation capacity. **(A)** By size of the research system. **(B)** By geographic region. Sources: Elaborated by authors based on Schwab (2018), Schwab (2019), Agricultural Science and Technology Indicators (2022), FAO (2022), SCImago (2022), United States Department of Agriculture, Economic Research Service (2022), and World Bank (2022).

reach of the value chain. As mentioned above, an index measuring changes in diets is included to capture changes on the demand side of the system.

The second step is to develop a measure of innovation capacity at the country level. Factors associated with innovation capacity include education and human capital; research investment and research quality; innovation policy and environment; and the quality of political and innovation institutions. The final step consists of systematic comparisons of countries with large and small agricultural research systems to find the relationship between the size of a country's research system, the level of development of its food system, and its overall capacity to innovate. Detailed information on the indicators used to build the food system development index (FSDI) and the index of innovation capacity (IIC) and on the approach used is included in the Supplementary material to this article.

4. Results

The average values of the FSDI and IIC indices for HICs and LMICs are presented in Figure 6. The median values of the two indices divide Figures 6A, B in quadrants of low-low, low-high, high-high, and high-low food system development and capacity to innovate, respectively. As expected, Figure 6A demonstrates a high and positive correlation between the development of a food system and a country's capacity to innovate. About 80% of the points representing countries in the figure are displayed along a fitted line with a positive slope, with half of these points in the low-low quadrant and the other half in the high-high quadrant. The remaining 20% of countries are distributed equally between the low-high and high-low quadrants. What is most revealing about Figure 6A is that two-thirds of the countries with small national agricultural research systems (35 out of 53) are in the low-low quadrant, while only one out of 8 large-sized systems and two out of 11 medium-sized systems find themselves in this quadrant. This means that countries in the Large group are not only investing more in agricultural R&D, but they are also doing so in a more favorable environment, with higher prospects of transforming research outputs into innovations.

Figure 6B repeats the same scatterplot, but this time the countries are depicted by geographic region instead of the size of their research systems. The figure reveals that more than 60% of the countries in the low-low quadrant (24 out of 38) are SSA countries. It also shows that all East and Southeast Asian (ESEA) countries except one (Myanmar) are on or above the fitted line, while most LAC countries are below this line. For example, among countries with a FSDI greater than the medium value in Figure 6B, there are four ESEA countries and 14 LAC countries. While all four ESEA countries are above the fitted line, only two of the 14 LAC countries are. This indicates that at the same level of development of the food system, ESEA countries have a higher capacity to innovate than LAC countries.

Of interest is the group of countries in the low-high quadrant in Figure 6B. These nine countries show a high capacity to innovate, despite a relatively low level of development of their food systems. Four of these countries—Botswana, Kenya, Namibia, and Rwanda—are in SSA. Other low-high countries include Indonesia, India, Morocco, the Philippines, and Sri Lanka.

4.1. Development of the food system and innovation capacity

Table 2 presents more detailed results of the FSDI and its components for countries grouped by the size of their research system, revealing systematic differences in the demand and supply components of the FSDI between countries in the Large and Small groups. On average, countries in the Small group consume less animal protein, suggesting that income growth, urbanization, and the diet changes associated with them occurred earlier or are taking place faster in Large countries. Important supply-side differences between the Large and Small groups were observed as well. The capital intensity in agriculture, measured as the use of capital inputs per worker, is almost 30% lower in the group of Small countries compared to the group of Large countries. Note,

TABLE 2 The Food System Development Index and its components for HICs and LMICs grouped by the size of their agricultural research systems, average values for 2011–2016.

		Low- and middle-income					
	High-income	Large	Medium	Small	Diff. small-large (%)	*p*-value[(a)]	
FSDI	**0.82**	**0.59**	**0.51**	**0.43**	**−44.2**	**0.004**	***
Diet	*0.79*	*0.46*	*0.35*	*0.28*	*−65.4*	*0.047*	**
Diet diversity	0.83	0.52	0.45	0.42	−24.9	0.256	–
Animal protein	0.78	0.44	0.28	0.21	−108.7	0.040	**
Supply index	*0.79*	*0.62*	*0.57*	*0.44*	*−33.5*	*0.000*	***
Capital intensity in agriculture	0.85	0.66	0.59	0.47	*−29.1*	*0.000*	***
Labor productivity	0.37	0.09	0.04	0.03	−195.4	0.172	-
Fertilizer/worker	0.23	0.05	0.02	0.01	−380.5	0.062	*
Pesticide/worker	0.21	0.12	0.02	0.03	−272.2	0.275	-
Herbicide/worker	0.14	0.06	0.01	0.02	−271.4	0.203	-
Feed/worker	0.23	0.02	0.01	0.01	−123.8	0.259	-
Machinery/worker	0.40	0.02	0.02	0.01	−173.4	0.254	-
Irrigated area/worker	0.22	0.05	0.04	0.02	−125.3	0.239	-
Value chain development	0.81	0.73	0.7	0.54	*−37.8*	*0.000*	***
Quality of local supply	0.85	0.72	0.74	0.64	−14.4	0.019	**
Cluster development	0.78	0.76	0.72	0.6	−28.8	0.002	***
Breadth of the value chain	0.75	0.65	0.61	0.54	−21.9	0.006	***
Product sophistication	0.79	0.63	0.59	0.49	−30.9	0.000	***
Extent of marketing	0.83	0.72	0.7	0.58	−26.8	0.002	***
Formal grocery sector	0.89	0.89	0.86	0.42	−125.5	0.002	***

Sources: Elaborated by authors based on Schwab (2019), Agricultural Science and Technology Indicators (2022), FAO (2022), and United States Department of Agriculture, Economic Research Service (2022).
[(a)] Differences could be significant at the 10 (*), 5 (**), or 1% level (***).
The bold values in the first row refer to the total index.
The total index is built by aggregating different sub-indices (in italics).

however, that there is great variability and no significant differences between groups of countries in the use of individual inputs per worker except fertilizer, which is used more intensively in Large countries. In contrast, significant differences between the Large and Small groups of countries were observed in all indicators that quantify the development of the value chain. This suggests that the development of longer value chains and the specialization in the chain's downstream segments is more prominent in Large countries than in Small countries.

Table 3 shows the IIC index and its subindices measuring a country's capacity to innovate. The results show large variations between countries with large and small research systems that are particularly significant when it comes to human capital and research capacity. Countries with small research systems have lower enrollment at all levels of education, especially in tertiary education where the value of the sub-index in countries with small research systems is less than half (0.156) than the value in the Large group (0.322).

Research capacity and its subindices in Table 3 gauge a country's overall performance in science including the number of publications in engineering, computer science and biochemistry, genetics, and molecular biology, as well as the H-index—a metric for evaluating the performance and impact of scholarly output, which measures the quantity and quality of publications in each of these areas. The H-index for biochemistry, genetics, molecular biology, computer science, and engineering in countries with large research systems is six times larger than the same index in countries with small research systems. The value of the index measuring the number of scientific publications per person in the population aged 15–64 is nearly 20 times higher in Large countries (0.039) than in Small countries (0.002). This indicates a much stronger development of science and of the scientific community in Large countries, which is expected to have positive spillovers to R&D in agriculture. Nonetheless, the gap in research output between large LMICs and HICs remains large, with HICs producing more than 10 times more publications on a per capita basis than Large LMICs.

Table 3 also illustrates significant differences of about 60% in the innovation environment between countries with small and large systems. This means that countries in the group of small systems demonstrate lower competition in local markets, more expensive financial services, sparser access to credit, and lower

TABLE 3 The index of innovation capacity (IIC) and its components for HICs and LMICs grouped by the size of their agricultural research systems, average values for 2011–2016.

		LMICs					
	HICs	Large	Medium	Small	Diff. small-large (%)	p-value[b]	
Index of innovation capacity	**0.555**	**0.392**	**0.340**	**0.270**	**−45.3**	**0.009**	***
Human capital	*0.735*	*0.506*	*0.408*	*0.358*	*−41.5*	*0.001*	***
Primary enrolment	0.932	0.917	0.694	0.712	−28.7	0.000	***
Secondary enrolment	0.697	0.491	0.394	0.278	−76.6	0.000	***
Tertiary enrolment	0.685	0.322	0.251	0.156	−106.5	0.026	**
Years of schooling	0.825	0.534	0.468	0.385	−38.5	0.011	**
Quality of education	0.645	0.426	0.384	0.335	−27.3	0.284	-
University-industry collaboration	0.674	0.512	0.419	0.289	−76.9	0.008	***
Research capacity	*0.403*	*0.229*	*0.148*	*0.074*	*−208.6*	*0.003*	***
Scientific papers/population[a]	0.404	0.039	0.012	0.002	−1,524.0	0.058	*
H-index Biochemistry, genetics, and molecular biology	0.336	0.181	0.101	0.031	−480.2	0.004	***
H-index Computer science	0.273	0.176	0.087	0.019	−812.7	0.008	***
H-index Engineering	0.328	0.235	0.121	0.028	−735.1	0.006	***
Innovation environment	*0.613*	*0.486*	*0.431*	*0.305*	*−59.2*	*0.033*	**
Innovation policy	*0.572*	*0.447*	*0.451*	*0.367*	*−21.7*	*0.087*	*
Quality of institutions	*0.454*	*0.292*	*0.262*	*0.249*	*−17.4*	*0.259*	-

Sources: Elaborated by authors based on Schwab (2019), Agricultural Science and Technology Indicators (2022), SCImago (2022), and World Bank (2022).
[a]Refers to published scientific papers in engineering, computer science and biochemistry, genetics, and molecular biology.
[b]Differences could be significant at the 10 (*), 5 (**), or 1% level (***).
The bold values in the first row refer to the total index.
The total index is built by aggregating different sub-indices (in italics).

R&D investment and staff training, all of which are factors that are congruent with a less developed and less competitive private sector.

4.2. Productivity, costs, and scale of agricultural research

Table 4 compares the agricultural research indicators of the average country with large, medium, and small R&D systems, providing descriptive statistics on agricultural R&D investment, the total number of agricultural researchers, and enrollment in tertiary education. The table shows that countries with small systems spend on average 43 million PPP dollars per year on agricultural R&D and employ 293 full-time equivalents (FTE) researchers. This compares to 353 million dollars and 1.3 thousand researchers in countries with medium-size research systems, and close to 2.0 billion dollars and 13,000 researchers in countries with large agricultural research systems.

The number of published articles in agricultural and biological science is used in Table 4 as an indicator of the scientific production of research systems. Publications are only one type of research output, others being new crop varieties, improved livestock breeds, new inputs, and intangibles like new processes and more efficient ways to allocate resources and manage the production process. Data on these other research outputs are not available for country comparisons at this level, but it is assumed that scientific outputs like published articles are a by-product of research on new technologies and reflect the productivity and quality of the research being conducted in the country. In that respect, they are a useful indicator for this analysis. The number of published articles in agricultural and biological science per million dollars spent on agricultural R&D totaled nearly 8.0 in HICs, 3.6 in both Large and Medium LMICs, and 2.8 in Small LMICs. Researchers in countries with large research systems published on average four times more articles per year than their colleagues in countries with small research systems.

These differences in productivity and the cost of research outputs cannot solely be attributed to differences in the size of the research system. This is evident from the comparison of the number of articles per million PPP dollars spent on agricultural research between HICs and LMICs. The agricultural research system is larger in the average LMIC than in the average HIC, but R&D spending per publication in HICs is only half the LMIC (and one-third of the average Small LMIC).

One of the explanations for the differences in productivity and research costs between HICs and LMICs beyond size is the quality and development of the national scientific research system. Note that the average HIC employs almost 90,000 FTE researchers across all disciplines for every million people enrolled in tertiary education, compared to 30,000 in the average LMIC and 18,000 in the average Small LMIC. This can be an indication that agricultural

TABLE 4 Agricultural R&D input and output indicators of HICs and LMICs grouped by the size of their research systems, 2011–2016.

	HICs	LMICs	Low- and middle-income		
			Large	Medium	Small
Public agricultural R&D spending (millions of 2011 PPP dollars)	660	792	1,980	353	43
Number of researchers, all disciplines (FTEs)	161,438	94,398	252,397	27,986	3,812
Number of agricultural researchers (FTEs)	n.a.	4,881	13,045	1,306	293
Published articles in agricultural and biological science	5,229	2,865	7,211	1,263	121
H-index in agricultural and biological science	300	134	202	142	59
Quality-adjusted articles published	5,229	1,283	4,855	597	24
Published articles per million dollars in ag R&D	7.9	3.6	3.6	3.6	2.8
Quality-adjusted articles per million dollars in ag R&D	7.9	1.6	2.5	1.7	0.6
Articles per agricultural researcher	n.a.	0.59	0.55	0.97	0.41
Quality-adjusted articles per agricultural researcher	n.a.	0.26	0.37	0.46	0.08
Enrollment in tertiary education (%)	n.a.	24	32	25	16
Researchers all disciplines/million people enrolled in tertiary education	89,811	30,018	32,527	18,447	18,011
Researchers in agriculture as a percentage of total researchers	n.a.	5.2	5.2	4.8	7.7
Number of countries	26	72	8	11	53

Sources: Elaborated by authors based on United Nations Educational, Scientific and Cultural Organization (2018), Agricultural Science and Technology Indicators (2022), SCImago (2022), and World Bank (2022).

research in HICs benefits from a higher overall level of science development, a greater critical mass, and better and more effective research networks. Evidence of these differences is the impact and quality of research measured by the H-index for agricultural and biological science. The value of the index is 300 in the average HIC, 134 in the average LMIC, 202 in the average Large LMIC, and only 59 in the average Small LMIC. Adjusting the number of publications proportionally by "quality" using the H-index further enlarges the research productivity gap measured by publications per researcher or per dollar spent between HICs and Large LMICs. In quality-adjusted terms, the average LMIC publishes 1.6 articles per million dollars spent on agricultural R&D compared to 7.9 articles in HICs and just 0.6 articles in the average Small LMIC.

Results so far have shown that low research productivity is prevalent among countries with small agricultural research systems. Two main factors are associated with low productivity in research: the presence of economies of scale in the production of knowledge and the quality of research and human capital at the national level. In what follows, we look in more detail at these two factors and examine the structural nature of low productivity and underinvestment in agricultural research in countries with small research systems.

Figure 7 plots the number of published articles in agricultural and biological science against agricultural R&D investment. Outputs increase exponentially when countries invest more than 100 million PPP dollars per year, and differences between countries investing more than 100 million dollars per year and those investing less are highly significant. The average spending per published article in countries investing <100 million PPP dollars in agricultural R&D was 514,000 dollars. The equivalent for countries spending more than 400 million PPP dollars was 308,000 dollars and only 123,000 dollars in HICs. Although these numbers only refer to published articles, there is evidence that they also apply to other research outputs. For example, Jin et al. (2005) found strong economies of scale for both wheat and maize research institutes in China. Their results show that if the number of new varieties produced increases by 10%, research costs increase by no more than 3.2%.

Despite the limited resources that Small LMICs allocate to agricultural research, they still need to spread these resources across a similar number of research areas and activities as countries with larger research systems, limiting the breadth and quality of research and resulting in low critical mass in specialty areas. Figure 8 shows that the number of researchers in countries with small research systems is only a fraction of that in countries with large research systems. For example, while the average Large LMIC allocates more than a thousand researchers to livestock and 600 researchers to cash crops, those numbers in Small LMICs average only 69 and 32, respectively.

At present, agricultural research in LMICs must respond to an ever-increasing demand that includes increased productivity and output quality; the development of new technologies that make sustainable use of natural resources; adaptation to and mitigation of climate change; responding to shifting consumer demands in terms of diets and food safety; and satisfying the demand for new product characteristics demanded by food processing industries, transportation and distribution systems, retailers, or by consumers in export markets. In addition, donors and other stakeholders are demanding that R&D contributes to poverty and inequality reduction and nutritional goals; and even that R&D strategies aimed at poverty reduction must take a broad variety of smallholders with very different resources, livelihoods, and needs into account (see Hazell, 2019 and the discussion in Tomich et al., 2019a).

These ever-increasing demands on research systems do not take into consideration the challenges that LMICs are facing to increase

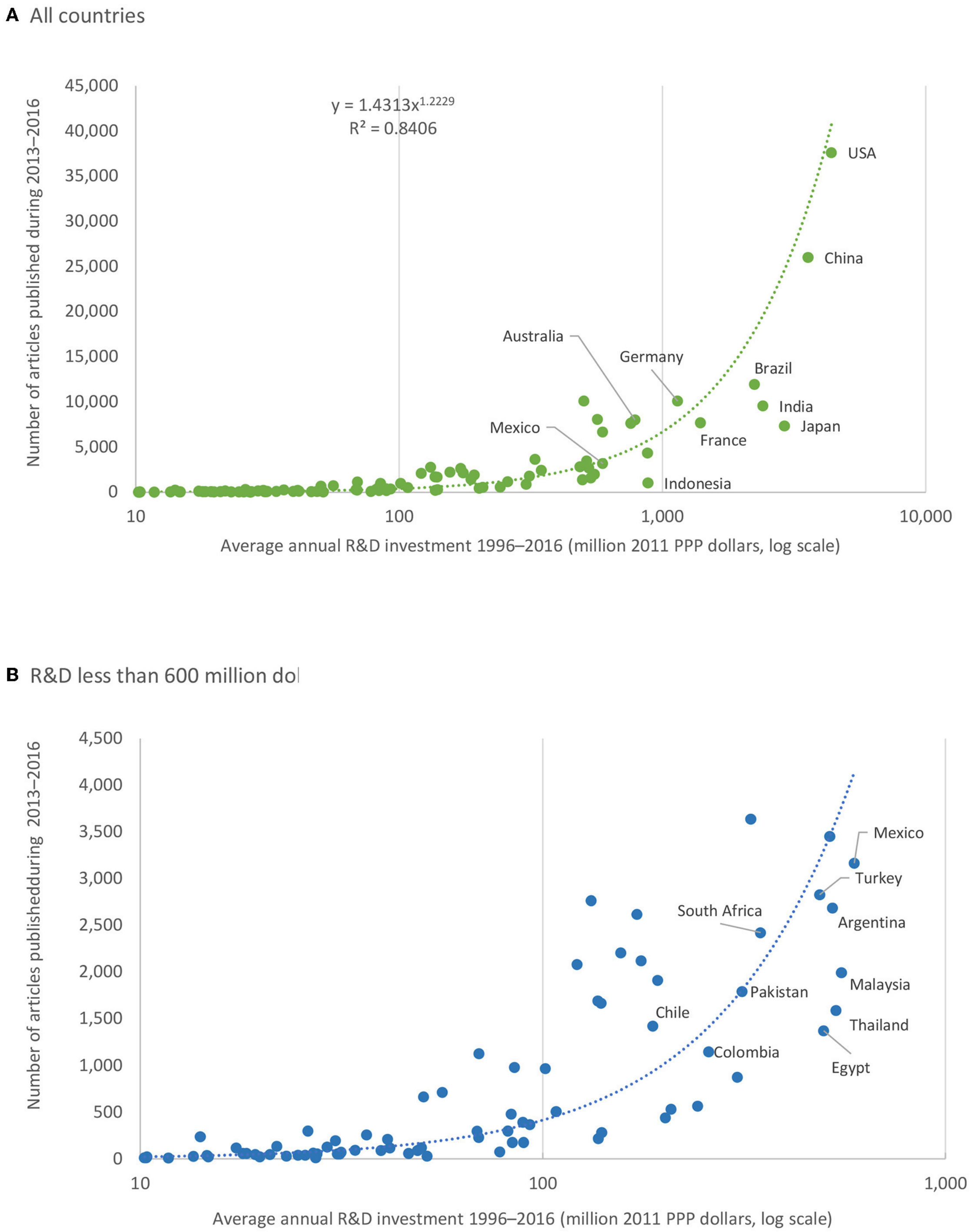


FIGURE 7
Size of the agricultural research system measured in dollars of R&D spending vs. the number of scientific publications in agricultural and biological science. **(A)** All countries. **(B)** Countries investing less than 600 million. PPP$ in agricultural research. Sources: Elaborated by authors based on Agricultural Science and Technology Indicators (2022) and SCImago (2022).

R&D investment. Any attempt to increase R&D investment in countries with small research systems is faced with structural constraints that can contribute to increased research costs and inefficiencies. Agricultural research represents only a part—in many countries a small one—of the national scientific research system, which in turn is highly dependent on the extent and quality of the education system. Low years of schooling, low enrollment rates, and low quality of education affect the quality of research by constraining the overall supply of researchers in all areas, including agriculture, and could result in increased

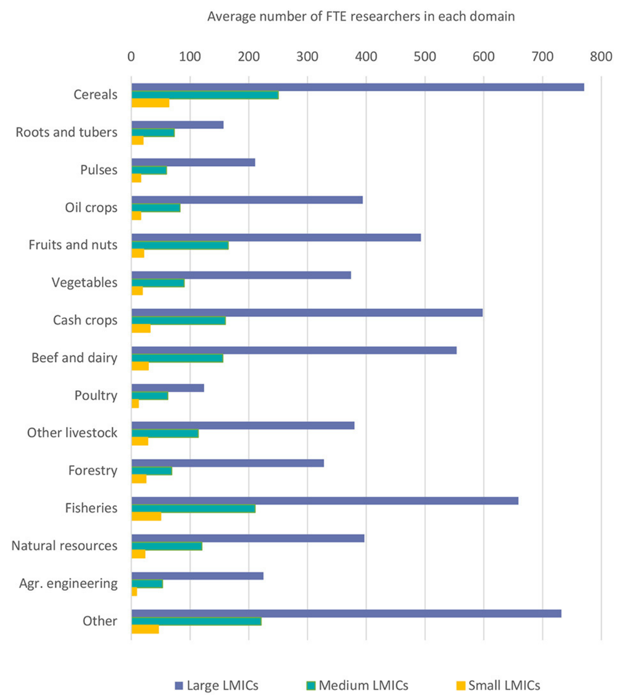


FIGURE 8
Average number of FTE researchers allocated to different research activities in LMICs with large, medium, and small agricultural research system, 2011–2016. Source: Elaborated by authors based on Agricultural Science and Technology Indicators (2022).

salary costs rather than improved research capacity (Goolsbee, 1998).

To get a better sense of the structural constraints faced by LMICs when it comes to increasing agricultural R&D, we regress agricultural R&D against different structural variables based on the following three assumptions. First, R&D spending on agriculture should be proportional to the total number of researchers across all disciplines. This is trivial given that the number of researchers in agriculture is a fraction of researchers in all disciplines, and that the salary costs of researchers are a major component of agricultural R&D spending. Second, the number of researchers in all R&D disciplines should be proportional to the number of people enrolled in tertiary education, as qualified scientists are an important output of the education system. Finally, the number of people enrolled in tertiary education is, by definition, a proportion of the number of people aged 18–24. What is important here is that the size of this proportion depends on the extent and development of the education system and the number of years of schooling, which in turn depend on a country's income level and other factors correlated with economic development. Based on these assumptions, the top half of Table 5 shows the results of regressing the number of researchers in all R&D disciplines against enrollment in tertiary education and related variables, while the bottom half presents coefficients from regressing spending in agricultural R&D against the total number of researchers across all R&D disciplines and other structural variables related to the development of the research system. As the log of the variables is used in the regression, the coefficients in the table express the percentage change in the dependent variable as the result of a 1% change in the independent variables.

Results in Table 5 show that there is a high correlation between the total number of researchers in all scientific research disciplines and the number of people enrolled in tertiary education (Model 1a). The coefficient indicates that a 1% increase in the number of people enrolled in tertiary education results in a 1.07% increase in the number of researchers. Model 2a replaces the number of people enrolled in tertiary education (N_{E3}) with the total population aged 18–24 (P_{18-24}) and the percentage of people enrolled (E%), given that, by definition, $N_{E3} = (P_{18-24} \times E\%)$. Unlike the number of people aged 18–24, the proportion of people enrolled does not depend on the size of the population, but rather on income and economic development. Model 2a shows that when controlling for the size of the population, a 1% increase in the rate of enrollment in tertiary education results in almost a 1.3% increase in the number of researchers. Given the high correlation between the percentage of enrollment and income level, Model 3a replaces enrollment with GDP per capita. Increasing per capita income by 1% results in an increase in the number of researchers by 1.4%. Models 4a and 5a include the share of agriculture in GDP, a variable that is negatively correlated with GDP per person. Model 5a is equivalent to Model 3a, but it includes the share of agriculture in GDP. The estimated coefficients of Model 5a indicate that when controlling for population and GDP per person, a reduction of 1% in the share of agriculture in GDP results in an increase of 0.5% in the number of researchers.

The bottom half of Table 5 shows coefficients and R^2 of regressing agricultural R&D spending against the total number of researchers in all scientific research disciplines. Model 1b shows that the correlation between agricultural R&D and the total number of researchers in all disciplines is high, with an R^2 of 0.81 and an elasticity of 0.66, meaning that a 1% increase in the number of researchers in all disciplines is expected to be associated with a 0.66% increase in agricultural R&D investment. Models 2b to 5b replace the number of researchers in all disciplines with the structural variables used as independent variables in the regressions in the top half of Table 5: the number of people aged 18–24, GDP per capita, and the share of agriculture in GDP. The H-index of biological, computer, and engineering sciences is also included as a measure of the quality and development of research in the country. Coefficients obtained with Model 5b indicate that agricultural R&D spending is positively related to a country's income level and the quality and development of its scientific research as measured by the H-index. The coefficient of the share of agriculture in GDP is positive but it is not significantly different from zero.

The evidence points to what appears to be three major challenges faced by small LMICs (which represent the majority of LMICs) to increase agricultural R&D investment notwithstanding widespread evidence of high rates of return. The first of these challenges is the underdevelopment of science and the small size

TABLE 5 Coefficients and R^2 obtained from regressing the log of the number of researchers in R&D in all disciplines and agricultural R&D spending against the log of different explanatory variables, average values 2011–2016.

Number of researchers in all disciplines										
	Coefficients									
	Model (1a)		Model (2a)		Model (3a)		Model (4a)		Model (5a)	
Persons enrolled in tertiary education	1.071	***	-		-		-		-	
Population aged 18–24	-		0.915	***	1.026	***	1.112	***	1.065	***
Enrollment in tertiary education (%)	-		1.290	***	-		-		-	
GDP per capita	-		-		1.427	***	-		0.991	***
Share of agriculture in GDP	-		-		-		−1.402	***	−0.502	**
Adjusted R^2	0.67		0.68		0.78		0.74		0.79	
Agricultural R&D spending										
	Coefficients									
	Model (1b)		Model (2b)		Model (3b)		Model (4b)		Model (5b)	
Researchers in all disciplines	0.660	***	-		-		-		-	-
Population aged 18–24	-		0.930	***	0.528	***	0.649	***	0.612	***
GDP per capita	-		0.875	***	-		0.313	***	0.444	***
H-index	-		-		0.787	***	0.561	***	0.608	***
Share of agriculture in GDP	-		-		-		-		0.263	-
Adjusted R^2	0.81		0.84		0.89		0.90		0.90	

Sources: Elaborated by authors based on United Nations Educational, Scientific and Cultural Organization (2018), Agricultural Science and Technology Indicators (2022), SCImago (2022), and World Bank (2022).
The estimated coefficient of the independent variable in the linear regression is significantly different from 0 at the 5 percent level (**) and 1 percent level (***).

of agricultural research systems in these countries, important factors that contribute to high average costs per unit of output and low overall research productivity. Second, LMICs with small agricultural research systems have a lower capacity to innovate, not only because of their less developed research and education systems but also because of a poor innovation environment, which in turn is correlated with the underdevelopment of the food system. Finally, most of the Small LMICs are SSA countries that have made slow progress in the process of structural transformation. They are still characterized by a high share of agriculture in employment and GDP, lower incomes, and traditional food systems with short value chains, poor market development, a weak private sector, lack of competition in domestic markets, and a large and diverse rural population that consists mostly of smallholders with poor links to markets. Small LMICs with a weak private sector and fragile links in the value chain face more difficulties and uncertainties to transform agricultural R&D into innovations, because as Reardon et al. (2019) put it, the private sector in the food system is the centerpiece of the supply chain that delivers innovations, determining the transformation of the entire food system.

In this context, it is not surprising to see underinvestment and slow growth of agricultural R&D in LMICs with small agricultural research systems. From a political perspective, two characteristics of agricultural research that affect public R&D investment are worth mentioning here: the time lag between allocating R&D funding and the realization of its outputs and subsequent returns; and the collective-action problem in R&D advocacy (Mogues, 2015). First, agricultural research is a long-term and risky activity with potentially high payoffs sometime in the future that could benefit a large and diffuse group of producers or consumers. These potential beneficiaries of research are unlikely to attribute benefits to research that was conducted years ago and transfer their voting allegiances accordingly. As a result, there is likely to be little incentive for governments to allocate a high share of the public budget to research (Harris and Lloyd, 1990).

The collective action problem in agricultural research refers to the costs of coordinating societal groups to advocate collectively for certain types of public investment or public policies. As argued by Benin et al. (2016), a small group of well-informed and educated beneficiaries with more economic resources is in a better position to assess which policies they should support, and which are detrimental to the group's economic interests, and coordinate actions to support policymakers who allocate public resources to the group's preferred activities. This is the opposite of what is observed in Small underinvesting LMICs with a large number of dispersed farmers that are less well-informed and educated, and who have fewer resources to financially support policymakers. Adding to this, and because agriculture represents a bigger share of the total economy in Small LMICs, meaningful investment in public agricultural research might impose a much higher cost on individual citizens, further diminishing the political appeal of supporting agricultural R&D. As Harris and Lloyd (1990) put it more than 30 years ago:

> "…private research is hampered by pervasive market failure, while public research is a long-term and expensive activity which is politically 'unprofitable.' It would be surprising if a combination of market failure and 'government failure' did not produce high rates of return."

Note that the characteristics of agricultural research mentioned above apply to all countries, but that the problem is exacerbated in Small LMICs because of weak research systems that increase the risk of research outputs and low capacity to innovate, which reduces the chances of transforming new knowledge into innovation and impact.

5. Discussion

This article revisited the debate around agricultural R&D underinvestment in LMICs with new data and methods to provide a better understanding of the structural factors behind agricultural R&D investment, innovation capacity, and food system development. The results revealed that the development of the food system is strongly correlated to a country's research and innovation capacity. Larger LMICs like China, India, Malaysia, Pakistan, and Thailand in Asia; Argentina, Brazil, Chile, Colombia, and Mexico in LAC, and South Africa in SSA, 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 play a more strategic role 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 SSA, have less developed food systems and a low capacity to innovate. The overall share of agriculture in these countries' GDP and employment 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 by 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 very 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 up to four times lower in HICs than in LMICs with small agricultural R&D systems, pointing to important inefficiencies in the latter group.

The fact that the results show that research and innovation capacity are highly correlated to the overall development of the food system is hardly surprising. However, it brings us back to the chicken-and-egg problem raised in the introduction of this article. Why do we continue to expect small developing economies to invest more in agricultural research if the R&D value chain in these countries faces potentially the same or more market and government failures than other investments that contribute to development like investments in infrastructure, education, and health? Or equivalently, why do we expect that an endogenous factor that is in part an explanation of underdevelopment, should become the solution to it? Gollin (2020) provides an answer to this question by referring to a recent set of papers analyzing the impacts of the Green Revolution. According to Gollin, those papers emphasize the fact that the Green Revolution served as an essentially exogenous productivity shock to recipient countries because of the very specific nature of the scientific advances involved. The presence of this exogenous shock could explain, at least in part, the success of the Green Revolution and how NARS, working with international centers, were able to overcome the limited availability of resources and low productivity of research in LMICs.

These developments of the past raise the question: Can the Green Revolution be repeated today if only the right technological innovations can be found? If the answer to this question is "yes," then the limited availability of resources and limited research capacity in LMICs would be less of a constraint than the results presented in the previous sections suggest. If the answer is "no," there is an urgent need to find new strategies for LMICs to access the technologies they need while simultaneously revamping agricultural research systems to increase their productivity and facilitate investment, given structural constraints. Gollin (2020) goes to great lengths to show that the historical experience of the Green Revolution is not replicable. This does not mean that new advances in biology and information technology would be less effective than the Green Revolution in the transformation of agriculture. On the contrary, the transformation of agriculture is already ongoing. The problem is that in the context of this new technological revolution in agriculture, the limited availability of resources and limited research capacity in LMICs threatens to widen the technological gap between poor and rich countries. This is because the nature of the scientific advances involved is quite different from those during the Green Revolution and also because of the significant changes in the economies of LMICs.

For a start, today's LMICs are more urbanized and less dependent on agriculture than the countries that benefited most from the early Green Revolution, while urban diets today are more diverse and less dependent on local supplies than was true for rural diets in Asia during the Green Revolution. Gollin (2020) argues, for instance, that urbanization and improvements in infrastructure have put African cities within plausible reach of food imports and made them far less dependent on their surrounding agricultural hinterlands. This has allowed urban consumers to rapidly shift from consuming foods produced in rural areas to consuming processed, prepared, and convenience foods that are mostly imported, a striking difference from Asia in the 1960's when urban consumers simply wanted larger quantities of grains. Producers, on the other hand, are often interested in reducing labor demand to free up time for off-farm activities rather than seeking yield increases. This process has led to an emerging disconnect between urban consumption and rural production, making agricultural growth more dependent on external markets for cash crops, rather than on domestic markets for food crops. Gollin concludes that in this context, the Green Revolution may not be easy to replicate. How can smaller LMICs then overcome the human capital, cost, and low productivity challenges related to the small scale of their agricultural research systems?

Several decades of persistent underinvestment despite widespread evidence of high rates of return shows that there is no simple formula to break the vicious circle of market and government failure in agricultural research. Economies of scale in knowledge accumulation and dissemination appear to be significant, so in most cases, LMICs aiming to conduct most of their research themselves may be too small to achieve an efficient scale in many, if any, of their R&D priority areas. Slow TFP growth of agriculture in these economies also suggests innovation problems beyond research. For example, limited adoption of improved crop varieties and livestock breeds, and practices could also indicate a broken R&D value chain where available technologies do not reach the end-user or, if they do, they are only partially adopted.

Offering solutions to a problem of this magnitude and complexity is well beyond the scope of this study, but results suggest some general principles to be applied in the future by small LMICs. First, the adoption of a food systems lens, as suggested by Reardon et al. (2019)—rather than a much narrower agricultural sector lens—is needed to provide new insights into the long-term impact of agricultural research, its synergies with multiple sources of activity within and outside agriculture, and its multiplying effects on growth. Second, a broad perspective of innovation is also needed given that agricultural research is one but not the only source of knowledge feeding the innovation process. As discussed by Harris and Kells (1997), if public and private R&D are seriously constrained, as in the case of LMICs with small research systems, policy actions designed to enhance the dissemination and diffusion of knowledge (spillover effects) may be a greater policy issue than the production of knowledge (R&D). In this respect, if large LMICs sustain fast growth of R&D investment in the coming decades, they can play a major role as sources of knowledge spillovers for small LMICs, making up for the dwindling investment in HICs.

As most countries will continue to conduct public R&D in agriculture, there is a need to increase the productivity of research by getting the most out of available resources and minimizing the negative effect of small-scale operations. Two complementary approaches could contribute to increasing productivity in research systems. The first one is to strengthen universities and government research institutions and innovation capacity in the private sector through policies and investments. A possible way forward is through a more strategic definition of research priorities, narrowing the research focus, organizing research around problems and not commodities or thematic areas, and adapting research institutions and governance of public research to these changes. The second approach is to increase coordination and integration between NARS and regional and global research organizations to overcome resource constraints, help avoid duplication, increase productivity of small-scale organizations, and thus make research more cost-effective. Defining research priorities is key, and prioritization necessarily implies the exclusion of everything that is not a priority for the country.

The issue of increasing coordination and integration of research organizations is not new. It has been argued before that closer integration of agricultural R&D at the subregional and regional level (through joint research programs and regional centers of excellence) is indispensable, given that it allows countries with less developed agricultural research and food systems to benefit from the gains made in countries with similar agro-ecological conditions and more advanced systems. However, the challenges to implementing an institutional reform, and coordinating national, regional, and international research organizations and other stakeholders with multiple demands and political interests could be a daunting task. Research integration and coordination bring a new set of issues to the table, that go from the contradictory research goals for regional, country, and local research, to governance, institutional and political conflicts in the organization of research and control and allocation of funding (see discussion in Sumberg, 2005). Implementing these institutional changes will require much more emphasis on collaboration, partnership, and strategic alliances with a high degree of stakeholder ownership around a shared vision.

For research coordination to work, Clark (2002) suggests that the interaction between partners should work like that of well-organized and cooperative "knowledge markets," which are central to the conception of innovation systems. According to Clark, formal, rulebound, and hierarchical systems where cooperation is viewed with resentment and suspicion, are unlikely to make a positive impact. In most cases, ineffective collaboration results in more organizations, requiring more overheads, chasing the same money, and fewer resources available to fund research. To avoid problems observed in the past, Tomich et al. (2019b) indicate that new institutions for research collaboration will require much flatter governance structures, linking local and global agendas, and enhancing national government interests and research capacities through multi-stakeholder partnerships rather than establishing new parallel and competing arrangements.

To conclude, the sustainable transformation of food systems in LMICs will undoubtedly need technical change and higher R&D investment. The question facing LMICs with small research systems is how to achieve this. Greater emphasis will need to be put on assessing where an additional dollar has the largest impact and what kind of institutions, networks, and mechanisms will help to effectively align country, regional, and global research goals to define, implement, and fund research agendas that will ultimately produce higher research impact.

We consider this study a first step in the analysis of R&D investment and innovation in LMICs. Based on our findings, future research will contribute to a better understanding of the relationships between structural factors determining agricultural research and the direction of causation between them through modeling and regression analysis.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AN-P and G-JS contributed to the design and implementation of the research, to the analysis of the results, and to the creation of the tables and graphs as well as the writing of the manuscript. Both authors contributed to the article and approved the submitted version.

Funding

This work was supported by the CGIAR Initiative on Foresight, the Micronutrient Action Policy Support (MAPS) project funded by the Bill and Melinda Gates Foundation, as well as contributions from the Inter-American Development Bank and the United States Agency for International Development to the International Food Policy Research Institute's (IFPRI's) Agricultural Science and Technology Indicators (ASTI) Program.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1051356/full#supplementary-material

References

Agricultural Science and Technology Indicators (2022). *ASTI Database*. Washington, DC: IFPRI.

Alston, J. M., Marra, M. C., Pardey, P. G., and Wyatt, T. J. (2000). Research returns redux: A meta-analysis of the returns to agricultural R&D. *Austral. J. Agri. Resour. Econ.* 44, 185–215. doi: 10.1111/1467-8489.00107

Beintema, N., Nin-Pratt, A., and Stads, G. J. (2020). *Key Trends in Global Agricultural Research Investment. ASTI Program Note*. Washington, DC: International Food Policy Research Institute.

Benin, S., McBride, L., and Mogues, T. (2016). "Why do African countries underinvest in agricultural R&D?" in *Agricultural Research in Africa: Investing in Future Harvests*, eds J. Lynam, N. Beintema, J. Roseboom, O. Badiane (Washington, DC: International Food Policy Research Institute, IFPRI), 109–138.

Clark, N. (2002). Innovation systems, institutional change and the new knowledge market: Implications for third world agricultural development. *Econ. Innov. N. Technol.* 11, 353–368. doi: 10.1080/10438590200000004

Diaz-Bonilla, E., Orden, D., and Kwieciński, A. (2014). *Enabling Environment for Agricultural Growth and Competitiveness: Evaluation, Indicators and Indices, OECD Food, Agriculture and Fisheries Papers, No. 67*. Paris: OECD Publishing.

Evenson, R. E. (2001). Economic impacts of agricultural research and extension. *Handb. Agri. Econ.* 1, 573–628. doi: 10.1016/S1574-0072(01)10014-9

FAO (2022). *Food and Agriculture Organization of the United Nations. FAOSTAT Database*. Available online at: https://www.fao.org/faostat/en/#data (accessed June, 2022).

Fuglie, K. (2016). The growing role of the private sector in agricultural research and development world-wide. *Glob. Food Secur.* 10, 29–38. doi: 10.1016/j.gfs.2016.07.005

Gollin, D. (2020). *Agricultural Productivity and Structural Transformation: Evidence and Questions for African Development. CEPR STEG Pathfinding Paper*. Available online at: https://steg.cepr.org/publications/agricultural-productivity-and-structural-transformation-evidence-and-questions-african

Goolsbee, A. (1998). *Does Government R&D Policy Mainly Benefit Scientists and Engineers? NBER Working Paper No. 6532*. Cambridge, MA: National Bureau of Economic Research.

Harris, M., and Kells, S. S. (1997). *Knowledge Spillovers, Location, and Growth: Theory and Evidence. Working Paper No. 6/97*. Carlton, VIC: Melbourne Institute of Applied Economic and Social Research.

Harris, M., and Lloyd, A. G. (1990). "The returns to agricultural research and the underinvestment hypothesis—A survey," in *1990 Conference (34th), February 13–15*. Brisbane, QLD: Australian Agricultural and Resource Economics Society.

Hazell, P. B. (2019). "Urbanization, agriculture, and smallholder farming," in *Agriculture & Food Systems to 2050. Global Trends, Challenges and Opportunities*, eds R. Serraj and P. Pingali (Singapore: World Scientific Publishing), 137–160. doi: 10.1142/9789813278356_0004

James, J. S., Pardey, P. G., and Alston, J. M. (2008). *Agricultural R&D Policy: A Tragedy of the International Commons*. Minneapolis, MN: University of Minnesota Department of Applied Economics: Staff Paper Series.

Jin, S., Rozelle, S., Alston, J., and Huang, J. (2005). Economies of scale and scope and the economic efficiency of China's agricultural research system. *Int. Econ. Rev.* 46, 1033–1057. doi: 10.1111/j.1468-2354.2005.00356.x

Mason-D'Croz, D., Sulser, T. B., Wiebe, K., Rosegrant, M. W., Lowder, M. W., Nin-Pratt, S. K., et al. (2019). Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger. *World Dev.* 16, 38–53. doi: 10.1016/j.worlddev.2018.12.006

Mogues, T. (2015). Political economy determinants of public spending allocations: A review of theories, and implications for agricultural public investment. *Eur. J. Dev. Res.* 27, 452–473. doi: 10.1057/ejdr.2015.35

Nin-Pratt, A. (2021). Agricultural R&D investment intensity: A misleading conventional measure and a new intensity index. *Agri. Econ.* 52, 317–328. doi: 10.1111/agec.12620

Porter, M. E., and Stern, S. (2001). National innovative capacity. *Glob. Competitiv. Rep.* 2002, 102–118.

Rao, X., Hurley, T. M., and Pardey, P. G. (2019). Are agricultural R&D returns declining and development dependent? *World Develop.* 122, 27–37. doi: 10.1016/j.worlddev.2019.05.009

Reardon, T., Echeverria, R., Berdegué, J., Minten, B., Liverpool-Tasie, L., Tschirley, D., et al. (2019). Rapid transformation of food systems in developing regions: Highlighting the role of agricultural research. *Agri. Syst*. 172, 47–59. doi: 10.1016/j.agsy.2018.01.022

Roseboom, J. (2003). *Optimizing Investment in Agricultural Research, or the Quest for Prosperity. Research Report 23*. The Hague: ISNAR.

Rosegrant, M. W., Sulser, T. B., Mason-D'Croz, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., et al. (2017). *Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio. Project Report for USAID*. Washington, DC: International Food Policy Research Institute (IFPRI). Available online at: http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/131144 (accessed March, 2022).

Schwab, K. (2018). The Global Competitiveness Report 2018. *World Economic Forum*. Available online at: https://www3.weforum.org/docs/GCR2018/05FullReport/TheGlobalCompetitivenessReport2018.pdf

Schwab, K. (2019). *The Global Competitiveness Report 2019*. World Economic Forum. Available online at: http://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2019.pdf (accessed March, 2022).

SCImago (2022). *SJR — SCImago Journal & Country Rank [Portal]*. Available online at: http://www.scimagojr.com (accessed November, 2021).

Spielman, D. J., and Birner, R. (2008). *How Innovative Is Your Agriculture? Using Innovation Indicators and Benchmarks to Strengthen National Agricultural Innovation Systems*. Washington, DC: World Bank. Available online at: https://documents1.worldbank.org/curated/en/696461468316131075/pdf/448700NWP0Box327419B01PUBLIC10ARD0no1041.pdf (accessed November, 2021).

Stads, G. J., Wiebe, K. D., Nin-Pratt, A., Sulser, T. B., Benfica, R., Reda, F., et al. (2022). "Research for the future: Investments for efficiency, sustainability, and equity," in *IFPRI book chapters, in 2022 Global Food Policy Report: Climate Change and Food Systems, Chapter 4, pages 38–47*. Washington, DC: International Food Policy Research Institute (IFPRI). doi: 10.2499/9780896294257_04

Sumberg, J. (2005). Systems of innovation theory and the changing architecture of agricultural research in Africa. *Food Pol*. 30, 21–41. doi: 10.1016/j.foodpol.2004.11.001

Tomich, T. P., Lidder, P., Coley, M., Gollin, D., Meinzen-Dick, R., Webb, P., et al. (2019b). Food and agricultural innovation pathways for prosperity. *Agri. Syst*. 172, 1–15. doi: 10.1016/j.agsy.2018.01.002

Tomich, T. P., Lidder, P., Dijkman, J., Coley, M., Webb, P., and Gil, M. (2019a). Agri-food systems in international research for development: Ten theses regarding impact pathways, partnerships, program design, and priority-setting for rural prosperity. *Agri. Syst*. 172, 101–109. doi: 10.1016/j.agsy.2018.12.004

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2018). *Montreal, the UNESCO Institute for Statistics (UIS) Statistics Database*. Available online at: http://data.uis.unesco.org/

United States Department of Agriculture, Economic Research Service (2022). *International Agricultural Productivity Database*. Available online at: http://www.ers.usda.gov/data-products/international-agricultural-productivity/ (accessed June, 2022).

World Bank (2006). *Enhancing Agricultural Innovation: How to Go Beyond the Strengthening of Research Systems*. Washington, DC: World Bank.

World Bank (2022). *World Development Indicators*. Available online at: http://datatopics.worldbank.org/world-development-indicators/ (accessed June, 2022).

TYPE Original Research
PUBLISHED 08 March 2023
DOI 10.3389/fsufs.2022.1013701

OPEN ACCESS

EDITED BY
P. V. Vara Prasad,
Kansas State University, United States

REVIEWED BY
Ignacio Antonio Ciampitti,
Kansas State University, United States
Prasanna H. Gowda,
Agricultural Research Service (USDA),
United States

*CORRESPONDENCE
Jaron Porciello
✉ jaron.porciello@nd.edu

SPECIALTY SECTION
This article was submitted to
Land, Livelihoods and Food Security,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 07 August 2022
ACCEPTED 28 December 2022
PUBLISHED 08 March 2023

CITATION
Porciello J, Lipper L and Ivanina M (2023) Using machine learning to evaluate 1.2 million studies on small-scale farming and post-production food systems in low- and middle-income countries. *Front. Sustain. Food Syst.* 6:1013701.
doi: 10.3389/fsufs.2022.1013701

Using machine learning to evaluate 1.2 million studies on small-scale farming and post-production food systems in low- and middle-income countries

Jaron Porciello[1]*, Leslie Lipper[2] and Maryia Ivanina[3]

[1]Lucy Family Institute for Data and Society, University of Notre Dame, Notre Dame, IN, United States, [2]Department of Agriculture and Resource Economics, University of California, Berkeley, Berkeley, CA, United States, [3]EPAM Systems, Minsk, Belarus

Recent developments have emphasized the need for agrifood systems to move beyond a production-oriented approach to recognize agriculture as part of a broader agrifood system that prioritizes livelihoods, social equity, diets, and climate and environmental outcomes. At the same time, the knowledge base for agriculture is growing exponentially. Using artificial intelligence and machine learning approaches, we reviewed more than 1.2 million publications from the past 20 years to assess the current landscape of agricultural research taking place in low- and middle-income countries. The result is a clearer picture of what research has been conducted on small-scale farming and post-production systems from 2000 to the present, and where persistent evidence gaps exist. We found that the greatest focus of the literature is on economic outcomes, such as productivity, yield, and incomes. There is also some emphasis on identifying and measuring environmental outcomes. However, noticeable data gaps exist for agricultural research focused on nutrition and diet, and gender and inclusivity.

KEYWORDS

agrifood systems, small scale farmers, evidence gaps, low-and middle-income countries, machine-learning, data science

1. Introduction

Decision-making is best informed by an up-to-date and comprehensive review of evidence on a particular topic. The ability to optimize insights from existing agricultural knowledge, and especially research that has explored agriculture's links to impacts on critical issues such as nutrition, climate change, and biodiversity, is key to informing ongoing policy decisions. While data-driven decision-making is widely promoted, especially in the context of complex development issues, the agrifood systems community still lacks critical data and tools that make summarizing data accessible and easily understandable.

Recent work and investment are helping to change this situation, especially for data collection at the country level. Programs like the 50 × 30 initiative[1] are closing the country-level data gap in agriculture and helping measure progress toward the Sustainable Development Goals (SDGs) by building strong nationally representative survey programs. The Food and Agriculture

1 https://www.50x2030.org/

Organization of the United Nations (FAO), likewise, supports the International System for Agricultural Science and Technology[2] to collect the data needed to measure SDGs (Lowder et al., 2021).

Solutions to domain-specific knowledge areas such as agriculture and livelihoods, environment and natural resource management, nutrition and health, and human capital and education are often found within the scientific literature. Expert knowledge, often in the form of scientific papers and other written analysis, is key to developing these solutions, as decisions need to be taken by integrating multiple information sources, incorporating accumulated experience, and weighing uncertainty. At the same time, the amount of available information is increasing exponentially—estimates suggest that human knowledge is doubling every 10–15 years—which makes it increasingly difficult to provide evidence-based interventions while avoiding the risk of confirmation bias or cherry-picking (Bornmann and Mutz, 2015; Bornmann et al., 2021).

Natural language processing (NLP) and machine learning can be highly effective at uncovering insights from large and representative datasets, helping us to make better use of the data in existing scientific publications. NLP is a branch of artificial intelligence that deals with the interpretation and manipulation of human language by computers. Machine learning is the use computers to learn and adapt without following explicit instructions by using algorithms and statistical models to analyze and draw inferences from patterns in data. Both machine learning and NLP approaches are designed to handle classification tasks with speed and accuracy, especially in datasets that lack metadata (Gil et al., 2014).

Recent work has allowed NLP to generate performing information extraction and summarization using relevant data from various sources. Such approaches have transformed how we can approach text-based classification. Pre-trained transform models such as Bidirectional Encoder Representations from Transformers (BERT), SciBERT and named-entity recognition with BERT are highly adept at capturing the context-dependent meaning of words even before additional training for other tasks that require expert input in the form of training data (Devlin et al., 2018; Beltagy et al., 2019; Luoma and Pyysalo, 2020). This can save significant time and money while delivering new insights.

Allowing for better understanding of the degree to which data and analyses are capturing systematic interactions is one of the most important features of ML and NLP approaches. This study reports on the use of machine learning to process and analyze 1.2 million summaries of past publications from a representative dataset of agricultural research focused on low- and middle-income countries. Its primary aim is the summarization of data to inform a series of open-ended questions that are difficult to answer because the data are scattered across millions of individual studies. These questions include:

- Who are the user groups included within studies?
- What are the most-studied interventions and outcomes by researchers?
- What is the research output across low- and middle-income countries?
- How much of the research is targeted at solutions for small-scale farmers and other agricultural actors vs. laboratory studies or other controlled environments?

2 https://agris.fao.org/agris-search/index.do

2. Methods

2.1. Approach: Mapping 1.2 million studies in agriculture

Recent work in measuring the output of overall scientific growth across certain fields has primarily focused on the comprehensiveness of large databases, such as Dimensions, Scopus, Web of Science and Microsoft Research (Bornmann et al., 2021). We targeted CABI's CAB Abstracts in part because of CABI's mission to identify and aggregate research from low- and middle-income countries, making it among the best databases in the world for our purposes. Similar analyses to ours, focused on agriculture and regional specific agricultural components, such as rice research in low- and middle-income countries, indicates the suitability of CAB Abstracts for such analyses (Rafols et al., 2020; Amarante et al., 2021).

We obtained 1.3 million citation records from data partner CAB Abstracts using the search strategy: (de: "climate") OR (de:biodiversity) OR (de: farm*) OR (de: agricultur*) OR (de:crop) OR [de:("food policy" or "agricultural sector" or "food security" or sustainabilit*" or "environment" or "nutrition" or "product*" or "yield" OR "hunger" or "agricultural policy" or "development aid")] yr:[2000 TO 2021].

We reduced 1.3 to 1.2 million by removing duplicate citations to produce our final dataset for analysis. No further reduction, using more specific inclusion criteria, was initiated was this effort. Artificial intelligence-assisted techniques were used to summarize abstracts by the categories are shown in Figure 1. NLP for text extraction and large-scale machine-learning language models were used to model the data for tasks associated with the identification of study user population, interventions, outcomes, geography, and crop type, among other elements. *A priori* determination of the categories was done in consultation with the expert-assembled Commission on Sustainable Agriculture Intensification (CoSAI). The prioritization on some specific tasks by the CoSAI groups enabled a more focused approach for the machine-learning.

2.2. Machine-learning to identify agricultural interventions, outcomes, and study design types

Identifying interventions, outcomes, study design types and more is normally undertaken during an evaluation of the evidence on a specific topic, such as part of an impact assessment or a systematic review, by domain experts looking through thousands of underlying original research papers. A well-trained machine-model can accelerate the labeling of many of these tasks. This study further contributes to exploring the role of computation to accelerate evidence and impact synthesis work in agriculture and climate change scientific publication datasets (Porciello et al., 2020; Callaghan et al., 2021).

Training data assembled from collaborative coding from previous exercises, including more than 2,500 high-quality papers from across

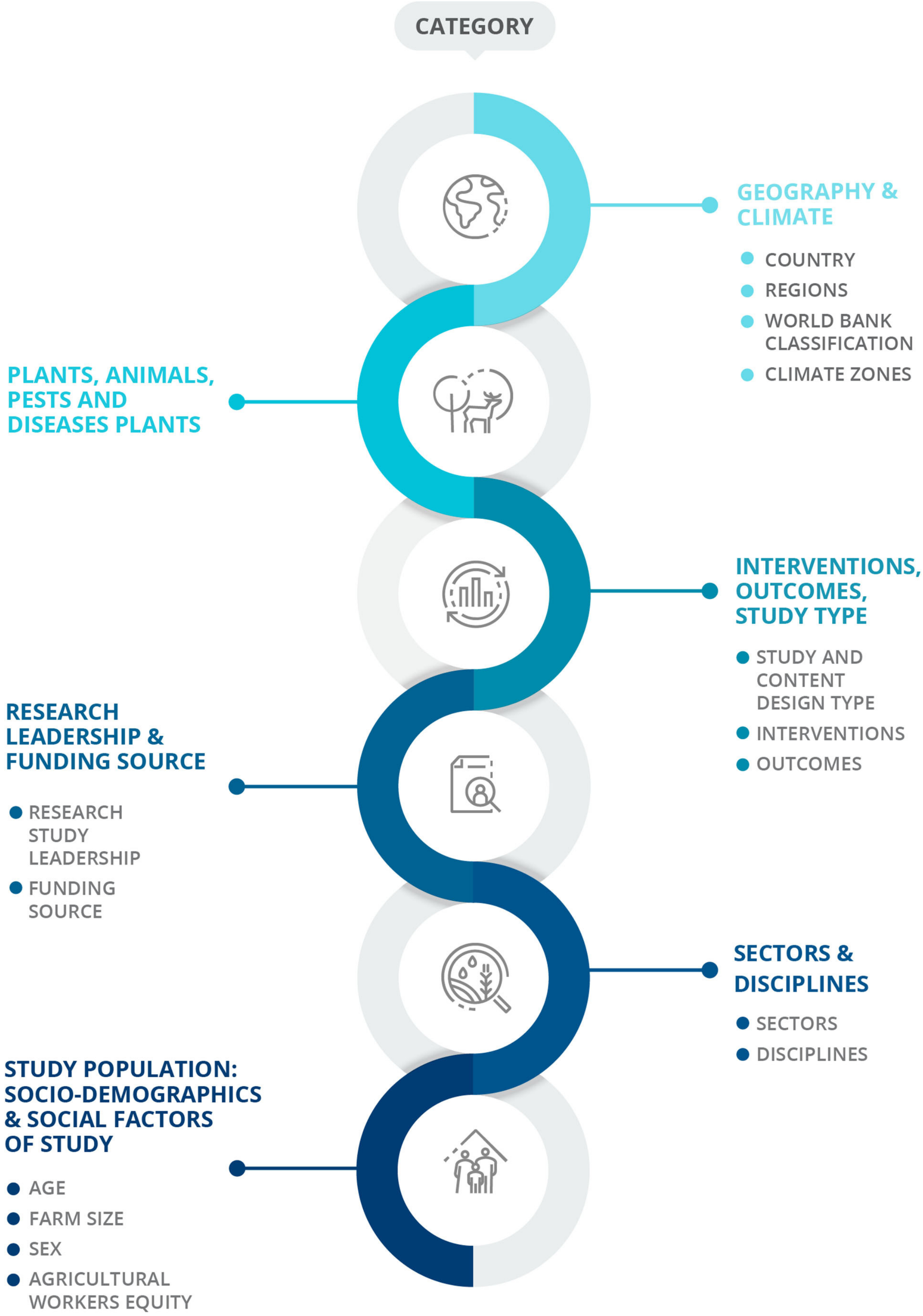


FIGURE 1
The various categories into which unstructured text summaries were analyzed using AI-assisted techniques.

the Ceres2030: Sustainable Solutions to End Hunger project, was used to enhance an artificial intelligence pipeline that supports classification and information extraction tasks (identified in Figure 1) for agriculture and related areas in international development (Acevedo et al., 2020; Baltenweck et al., 2020; Bizikova et al., 2020; Liverpool-Tasie et al., 2020; Nature, 2020a; Piñeiro et al., 2020; Porciello et al., 2020; Ricciardi et al., 2020; Stathers et al., 2020). In addition, the underlying models been continuously trained on tasks supporting diverse development literature as a result of other partnerships, including use in new domains such as water, hygiene, and sanitation, digital agriculture, and development and humanitarian assistance, and all of which required the identification of outcomes and interventions (Garbaro et al., 2020; Jardine, 2021; Porciello and Ivanina, 2021; Porciello et al., 2022).

Unlike health and medical sector, which maintains an International Classification of Health Interventions[3] through the World Health Organization (WHO), agrifood systems lack a similar standardized taxonomy of interventions. One most powerful structured collections of agricultural concepts, terms, definitions, and relationships—FAO's AGROVOC—defines an intervention simply as a "controlled price" (AGROVOC: AGROVOC Multilingual Thesaurus, n.d.). This definition is a sparse interpretation of the range of potential activities that can be used to support policies and programs to improve agrifood systems. Other organizations, including the OECD recommend expanding the interpretation beyond price interventions to include more agricultural, humanitarian and development sector activities (OECD, 2019).

We developed a proxy to inform how to approach an unstructured text corpus to identify literature that describes interventions but importantly, without necessarily using the term intervention. Training of the model for interventions included searching articles and summary data for synonyms of intervention and enhanced using Word2vec. Word2vec was chosen because of its more than decade-long history of performing NLP tasks to find syntactic and semantic similarities of words. Word2vec's shallow language model is appropriate for small and relatively heterogeneous datasets such as ours, and it has low computational costs, taking <1 day to learn high-quality word vectors from a 1.6-billion-word dataset. Similar models, such as Global Vectors (GloVe), could be used in conjunction with or instead of Word2vec with similar results, although training time might slightly increase (Sharma et al., 2017, p. 2). Using pre-trained Google News and Wikipedia Word2vec models, similar concepts to interventions for the agricultural domain were identified, including "program or programme," "strategy," and "government initiative" (Porciello et al., 2020). Next, to surface all potential and specific interventions, we incorporated a semi-unsupervised model-based approach *via* coreference resolution models to support NLP tasks by linking noun phrases with entities in the text. A training dataset that broadly represented how interventions were described in the literature as technological, socioeconomic, and ecosystem service interventions was applied. More description about these categories is provided in the results section. Next, we sought to surface and label how more specific interventions, such as drip-irrigation or solar-irrigation, could be represented and labeled as part of a narrow cluster of interventions, such as "irrigation" interventions.

Next, the model was trained to identify outcomes. Unlike interventions, there are standardized definitions for outcomes (Table 1 in Results). The model was trained to detect when an outcome was mentioned and had a relationship to narrow classes from the intervention. A single example consists of a sentence, an intervention from the ontology and/or plant, animal product from the AGROVOC dictionary, and an outcome from the sentence. When the model detects an outcome is connected with a particular intervention in the context of a sentence, it labels the citation with the appropriate outcome based on the general definition.

Both rule-based and transformer-based models were used for this task with similar results. A rule-based support-vector machines (SVM) was used in a semi-unsupervised approach to organize studies according to NLP-derived intervention, outcome, and study design type taxonomies. An SVM–k nearest neighbors–stochastic gradient boosting approach was used for classifying specific interventions, where all the supporting content (in this case, summary data) is examined in a vector space. The SVM is a supervised classification algorithm that learns by example to discriminate among two or more given classes of data, and they work well with high-dimensional data especially for smaller datasets. In addition, BERT-based models are designed for sentence level and token-level tasks and are useful for identifying relationships in small pieces of text. BERT models including base BERT, Roberta, Albert, SciBERT, and DistillBERT were tested. DistilBERT Named Entity Recognition (NER) uses the BERT architecture but performs knowledge distillation during the pre-training, allowing for lighter, faster and cheaper transformer model, and reduces the size of a BERT model by 40%. Due to the size of the labeled dataset, models were trained by freezing all layers (which is responsible for encoding the text) except the last two layers (where classification occurs).

Finally, study design types also lack common definitions. These were labeled using expert data and the transformer model SciBERT, which has been pre-trained on scientific articles (Beltagy et al., 2019). For other tasks, text extraction models, including pre-trained spaCy, specialized dictionaries, and ontologies of AGROVOC and the National Agricultural Library Thesaurus, were used to identify and label geography, plants, animals, diseases, research leadership and funding, and study populations.

3. Results

One of the most useful ways to report the findings of this analysis is through an evidence gap map (Figure 2), a visual and interactive tool that provides an overview of all evidence collected on a particular issue (Vincent et al., 2022). Evidence gap maps enable policy makers and practitioners to review findings, explore the quality of the existing evidence, and make evidence-based decisions in international development policy and practice. They also identify key "gaps" where little or no research has been published (Snilstveit et al., 2016).

The key components of an evidence gap map are interventions and outcomes. The evidence gap map identifies the most frequently studied interventions as determined by a threshold of at least 10,000 articles and categorizes them into one of three broad categories of agricultural research (socioeconomic, technological, and ecosystem services). Importantly, an evidence gap map does not prioritize or claim there is a single intervention that is "a silver-bullet" to support agricultural development outcomes. Rather, the intention is to surface volumes of research and where more, and less, emphasis has been placed.

3 https://www.who.int/standards/classifications/international-classification-of-health-interventions

TABLE 1 Outcomes, descriptions and definitions.

Outcome class	Description	Specific outcomes	Definition
Economic growth	Growth across all agriculture or food systems sectors and subsectors that improve the lives of farmers and food systems actors and their families through increases in income, productivity, employment, and practice change.	Income amount	Change in income
		Income diversity	Change in sources of income
		Productivity	Change in on-farm crop, labor or livestock productivity or value-chain productivity
		Yield	Change in yield from crop, livestock or foraging
		Adoption	Change in a user's adoption of management or technology related to other agricultural outcomes
		Market efficiency	Change in decision-making based on available, relevant market information
Healthy people	Ensuring reliable access to a sufficient quantity of affordable, nutritious food and food consumed is represented by different food groups	Dietary diversity	Change in dietary adequacy, including nutrient intake, nutrient adequacy index, and food-based diet quality index
		Food access	Change in an individuals' or households' ability to access food
		Food availability	Change in availability of food
		Malnutrition	Change in malnutrition status
		Wasting and stunting	
		Nutritious food availability	Change in availability or access to nutritious food
Healthy planet	The process of incentiving practices that emphasize environmental and planetary health	Environmental Sustainability	Change in sustainability of natural resource management such as water, forest or soil management e.g., reduced soil erosion, reduced tree cover loss or increased tree cover,
		Climate mitigation	Change in greenhouse gas emissions
		Change in capacity to adapt to the impacts of climate change	Adaptation and behavior change that respond specifically to impacts of climate change
		Biodiversity	Change in biological resources at genetic, species or ecosystem level (on farm or off-farm)
Gender & Inclusivity	The process of improving the terms of participation in society, particularly for people who are disadvantaged, through enhancing opportunities, access to resources, voice and respect for rights. This is measured through resulting from the support and inclusive design of all people, but in particular traditionally marginalized groups such as women and people with disabilities, as well as through increased decision-making.	Increased Knowledge	Change in knowledge about agriculture or food systems related content
		Women's empowerment	Change in women's ability to influence and make decisions independently
		Women's access to resources	Change in women's access to resources (e.g., credit, or inputs)
		Social inclusion	Change in obstacles that limit agency and decision-making capacity
		Social learning	Change in knowledge and practices through group and community engagement

Technological interventions constitute the use of practices and technologies (both direct and indirect) to support agricultural production and food systems (Acevedo et al., 2020; FAO, 2022a,b). Indirect uses include underlying technology such as biotechnology to improve seeds, whereas direct would be use of irrigation, mechanization, and inputs such as fertilizer. Socioeconomic interventions include market and finance interventions that contribute to accessing markets, credit or other financial products

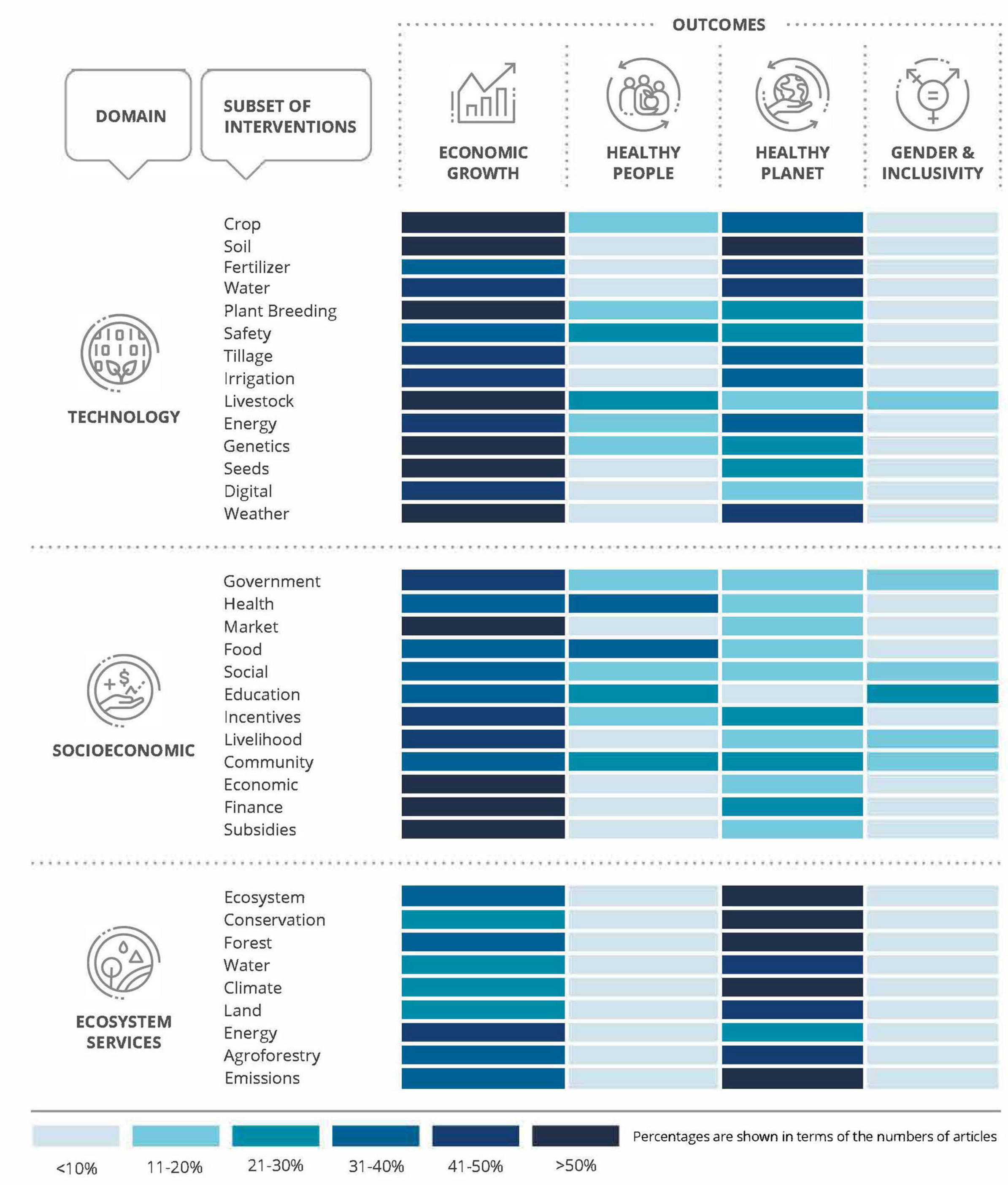


FIGURE 2
An intervention and outcome evidence gap map identifying the most frequently studied interventions and associated outcomes.

or investments in value chain development, as well as interventions that increase knowledge or awareness, transfer skills, and build capacities such as education (Liverpool-Tasie et al., 2020). This category also includes policy and government interventions, such as government, funder, or other organizational programs and policies to support farmers and agri-food system actors through incentives, or direct support, and includes interventions to improve inclusion of women and other marginalized groups (Barrett et al., 2020). Ecosystem services interventions focus on improving ecosystem services with regulating and supporting functions such as clean air, nutrient cycling, pollination, erosion control, carbon storage and more (Piñeiro et al., 2020). Additional analysis can be conducted to further sub-divide the categories for additional, discrete analysis.

The evidence gap map in Figure 2 shows the frequency of interventions per outcome, expressed as a percentage across the literature. For instance, over 50% of plant breeding interventions in the literature are associated with outcomes related to economic growth, whereas 11–20% are associated with nutrition outcomes, 21–30% with environmental outcomes, and <10% with women's empowerment and inclusion. Table 1 provides outcome descriptions and definitions.

The highest reported outcome is economic, such as productivity, yield, and incomes, in the literature. This reflects the fact that agricultural research and innovation literature has been largely focused on improving productivity of a small number of crops rather than focusing on other important aspects of crop research, such as dietary diversity (Serraj and Pingali, 2018). Some emphasis has been placed on on identifying and measuring environmental outcomes, including water use and health, across many of the intervention categories, especially those focused on ecosystem services.

Where the data gaps are more noticeable are regarding agricultural research focused on nutrition and diet, and women's empowerment and other inclusivity outcomes mentioned in the literature, such as increased knowledge obtained through training and education programs. For the latter, the gaps are widespread across all intervention categories.

Figure 3 provides a regional level overview of the publication trends focused on specific crops mentioned in title and abstract data. Table 2 provides a breakdown of the specific crops included in each category and their inclusion was determined *a priori* through consultation (as referenced in the introduction). Generalized terms such as cover crops, livestock feed crops, container plants, bee plants, beverage crops, and oils were excluded from the mapping because it was unclear from the summary what crops they referred to, and because they totaled fewer than 25,000 mentions. Each study was labeled with multiple labels, meaning that more than one relevant label could be applied. For instance, if a study focused on wheat, maize, and rice in Vietnam and Thailand, then the study would be counted as "1" in all subsequent categories.

China, Brazil, and India lead the way in publishing research outputs, but different countries and regions come into focus depending on the target crops, as highlighted by the maps in Figure 3. Perhaps as expected, countries that are home to a major international research center, such as the International Maize and Wheat Improvement Center in Mexico or the International Rice Research Institute in the Philippines, have a higher prevalence of research related to the specific crops being studied. Other grains that are important for food security, such as millet and sorghum, have a smaller cumulative total of around 10,000 articles.

The findings on study design types by research categories (Figure 4) show research activities that report on non-human experiments, such as field trials, laboratory, and simulation studies. A total of six labels were created to identify study population types: field study, experimental study, simulation/modeling study, narrative/review study, laboratory study, and observational studies. Each citation received only one study type. The categories along the Y axis are CABI Codes. CABI Codes is an index of 23 major subject areas related to the area of the citation, each with their own set of sub-codes (https://www.cabdirect.org/help/about-cabicodes.html). CABI codes are added by the vendor when an article is included in CAB Abstract database. This provides an existing, manually curated index of research topics that does not rely on machine-learning. The subject area of agricultural economics has the largest number of observational studies, followed by field crops, meteorology and climate, and water resources.

Finally, a multi-label approach to capture information about the study population communities, including when studies mention descriptions about age, sex, affiliation with indigenous communities or other, and agricultural workers, including farmers. Despite a generalized, multi-labeling approach, the data collection and reporting on user populations is very weak. Only about 25% of studies reported any information about a population of study. Though there may be widespread acknowledgment that women, farming communities and others in the agricultural workforce face significant challenges, there is a risk they will be undermined in these types of global assessments by weak data collection practices regarding demographics and other specific descriptions and/or underreporting in the literature (Teeken et al., 2018).

4. Discussion

4.1. Prioritizing research gaps

The way we think about agriculture is currently undergoing a major shift away from a focus on production and toward a broader understanding that puts agriculture in the larger context of an agrifood system with complex interactions between food production, processing, consumption, nutrition, social change, and climate change (Barrett et al., 2020; Lipper et al., 2020). This shift implies a need to rethink the role of agricultural research and development efforts, and push for innovations that go beyond productivity. There is a corresponding urgency to identify priority investments (Reardon et al., 2019; Laborde et al., 2020). To do so, however, we must have an adequate and accessible evidence base for understanding agricultural innovations and their potential in the context of a transformation.

Integrated approaches across interventions are more effective in achieving gains across the entire food system. Therefore, the relative scarcity of research emphasizing diet, nutrition, and women's empowerment relative to the long-standing priorities of productivity and yield in agricultural research should not necessarily lead us to conclude that some areas of research only need to "catch up" to others. Simply focusing on expanding the literature in one of the relatively under-researched areas will not address the yawning gap of evidence on the interactions that occur across various outcomes.

However, not all areas where there is a dearth of research can be treated equally or with the same urgency. There are many areas of research where we have gaps in the evidence on the impact of interventions on specific outcomes (Figure 3) but identifying where significant trade-offs between outcomes can arise from interventions is key in the context of analyzing the food system and its interactions (Fuso Nerini et al., 2018; Kroll et al., 2019). For example, the lack of research on fruits, vegetables, and more nutritious grains such as millet and sorghum (Figure 3), as well as accompanying post-harvest storage to ensure safety and reduce loss, is a gap in our understanding relevant not only to improving diets and addressing micro-nutrient deficiencies, but to gender and inclusivity, given the high rates of female participation in horticultural and post-harvest activities (Kennedy et al., 2017; Nordhagen, 2021).

There is too little data being reported in agrifood systems literature about study populations, and the impacts and uptake of innovations across small-scale farmers and their communities. Better identification of relevant characteristics of the people and

10.3389/fsufs.2022.1013701

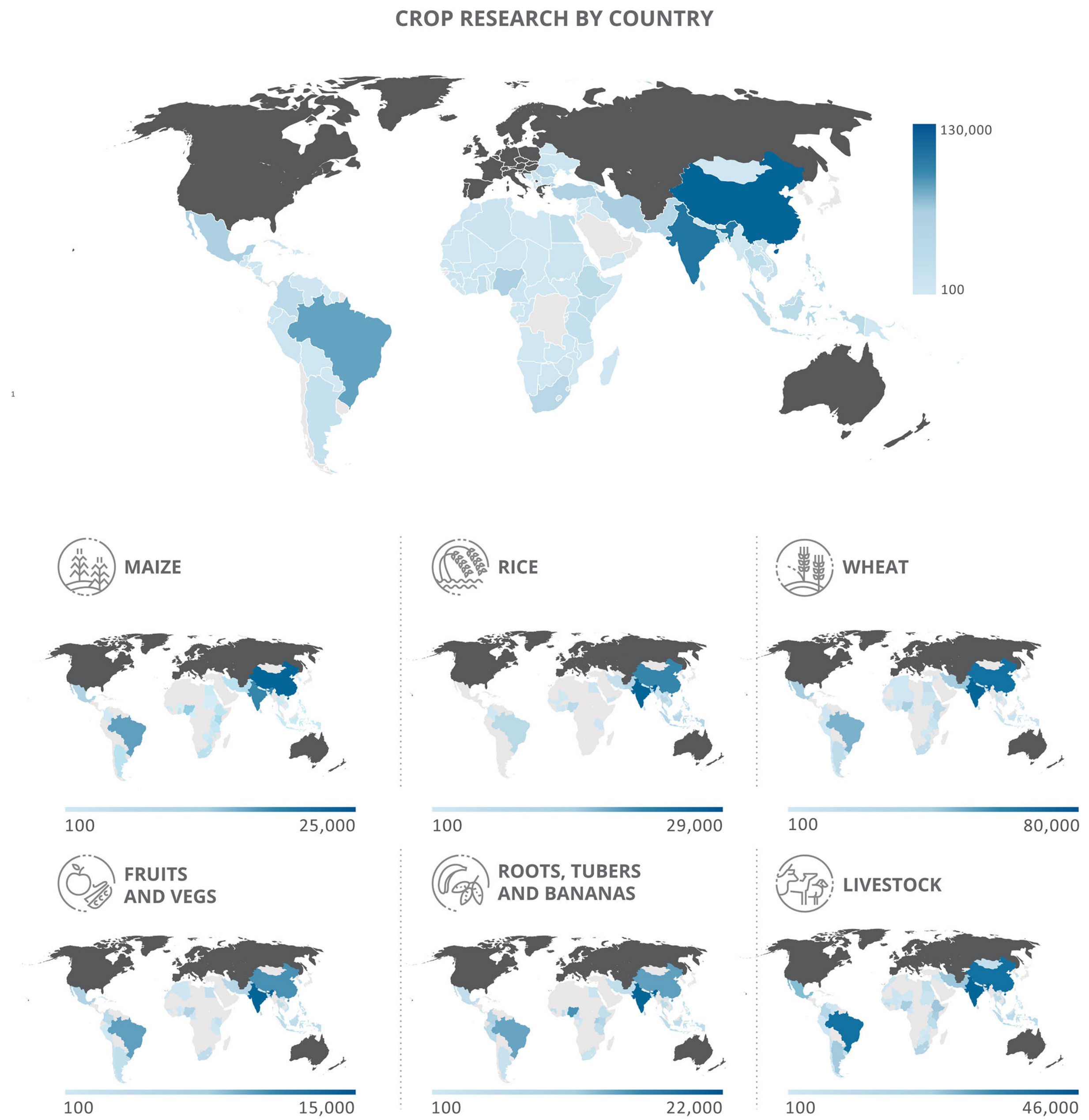


FIGURE 3
A country-level look at research production across specific crops.

TABLE 2 Crops per category.

Maize	Rice	Wheat	Fruits and vegetables	Roots, tubers, and bananas	Livestock
Maize (all variations, e.g., flint maize)FAO Cereal/Maize Sweet Corn *Zea mays*	Rice (all variations, e.g., wetland rice) Cereal/Rice *Oyrza* (all variations)	Wheat (all variations, e.g., winter wheat) Cereal/Wheat *Triticum* (all variations)	More than 100 individual fruit and vegetable crops were searched. The full list is included in the appendix.	Banana (all variations, including cooking banana) Cassava Yuca Yam Sweet potato Potato (all variations) Turnip Taro Rutabaga	Cattle Swine/Pigs Poultry (e.g., chickens) Domesticated Buffalo Sheep Goat Yak Zebu Horse Camel

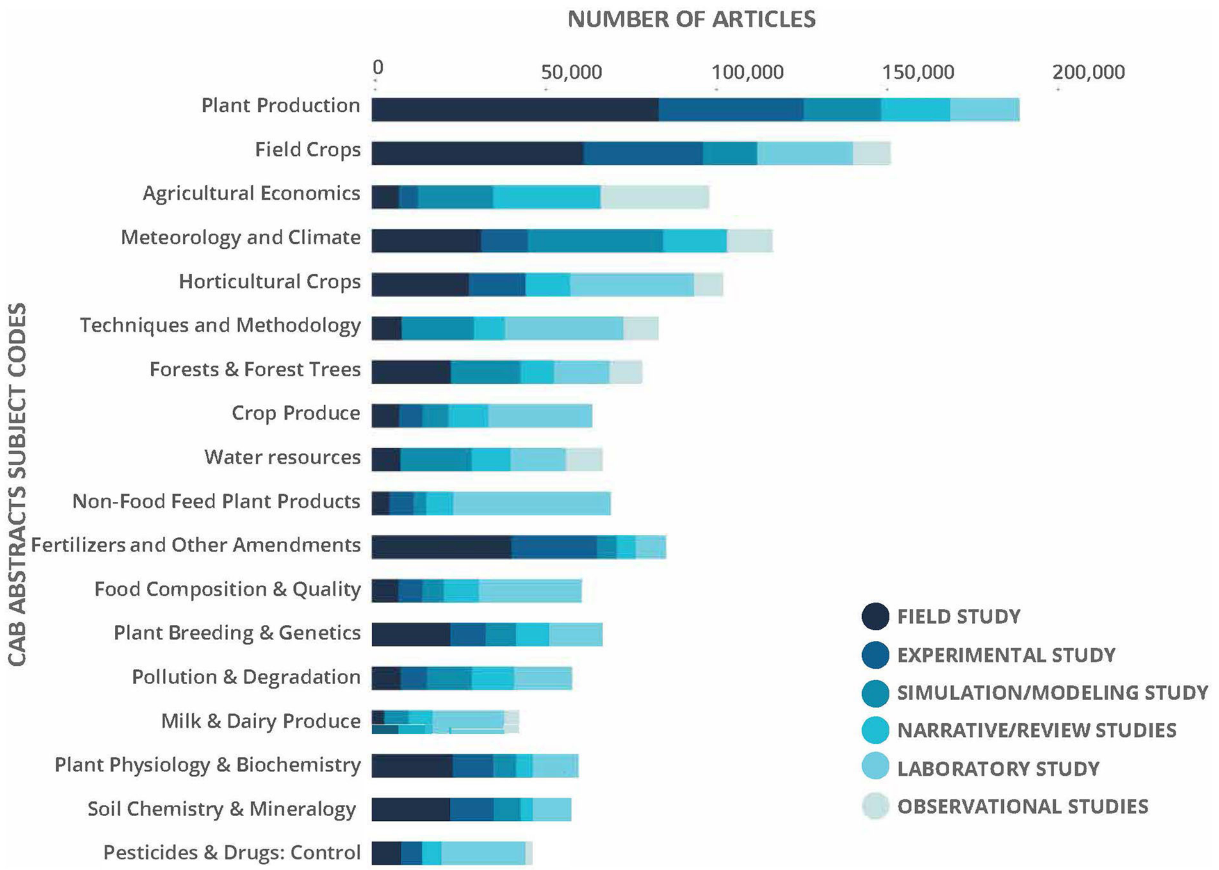


FIGURE 4
Study design and research topic areas.

communities involved in agricultural activities is essential to understanding the outcomes of interventions and the interactions that arise across different outcomes. Part of the issue is the extremely ambiguous descriptions of farmers and agricultural workers. These descriptions rarely include contextual clues about the type or size of farm they work on. Similar gaps were reported in another evidence analysis, which found that only 2–3% of studies across a portfolio of scoping reviews reported on the conditions and interventions of farmers in low- and middle-income countries (Nature, 2020b). Given that the emphasis of SDG 2 focuses on the conditions of poor farmers in low- and middle-income countries, high-impact, applied research to identify and report on successful programs across all outcomes in low- and middle-income countries is urgent.

Equally important for future of research is the capture of social equity and sociodemographic details that could underscore how barriers are systematic for some communities and not for others. Socioeconomic status, race, class, and gender can create interdependent systems of discrimination that reinforce the exclusion of some groups—particularly, but not only, women—from the benefits of certain programs and innovations. The ability to look at social factors as a system is essential to avoid tendencies to overgeneralize and assign certain characteristics to entire groups, such as elderly, youth or women (Sumberg and Hunt, 2019). A recent scoping review focused on digital agriculture identified that fewer than 30% of all studies reported socioeconomic and demographic data (Porciello et al., 2022). This shortcoming is of particular concern in the context of assessing multiple and potentially interacting outcomes from agricultural research. In a 2020 review of literature on factors influencing the adoption of sustainable agriculture, farmer characteristics—including asset levels, experience and risk preferences—were a key factor in explaining farmers' behavior, particularly where there were potential trade-offs between environmental and economic outcomes (Piñeiro et al., 2020). In discussing the reasons for the lack of progress in transforming small-scale agriculture, Woodhill et al. (2020) cite a lack of understanding of the diversity of characteristics and contexts of small-scale farmers is reported as a major factor. Here, again, the issue of multiple and potentially competing outcomes from agricultural change was important. As we look toward the future of research prioritization, equity outcomes need to become more pronounced (Davis et al., 2022; Laderchi et al., 2022).

In this respect agricultural and food systems studies fall well behind other disciplines, such as medicine and health. Coordinating bodies in health and medicine, such as Cochrane draft guidance and minimum standards for synthesis conduct, develop methodologies and training capacity, and commission and publish high-quality reviews. The absence of such coordination and synthesis in agricultural sciences has contributed to the evidence gaps mapped in this study. These gaps should no longer be ignored. Simply focusing on expanding the literature in one of the relatively under-researched areas will not address the yawning gap of evidence on the interactions that occur across various outcomes with interventions into any one piece of the system. Assessing progress on the myriad of impacts of what, where, when and why are often commissioned individually by donors with little opportunities for coordination. Moreover, despite the existence of gaps in data collection, such as the absence of sociodemographic data about farmers that we have highlighted above, the lack of an organizing body means that there currently exists no group to champion for long-term change in research practices, methodologies for synthesis conduct, and data collection.

The aim of this study is to uncover relevant insights across primary studies and used only summary title, abstract and other available metadata. However, what authors choose to emphasize in the title, abstract and other summary data is influenced by various editorial decisions between themselves and the journals publishing the materials. For instance, some journals may ask authors to refrain from mentioning too many details in the abstract, such as the user population of study, countries of focus, or specific plants. Access to the full text is needed to evaluate the claims made in the summary data, such as whether the interventions and outcomes recognized in the abstract are substantially supported with high-quality data in the study (Garbaro et al., 2020; Porciello and Ivanina, 2021; Porciello et al., 2022).

Evidence from the Covid-19 Open Research Dataset (CORD-19) demonstrates the value obtaining copyright and permissions clearance from commercial publishers to support text mining and NLP research on scientific papers. CORD-19 is an open access collection of more than one million scientific papers published between March 13, 2020–June 2, 2022 related to coronavirus with the full-text available for text-mining of nearly 370 K papers (Wang et al., 2020). The opportunity to read and rapidly discover insights from primary scientific research during Covid-19 is useful to all scientists and policy-makers, and CORD-19 computational tools for text-mining delivered additional, rapid insight on internationally collaborative work, and the contributions of funders, countries, institutions, and fields throughout the pandemic (Wagner et al., 2022).

A demand-driven approach to obtaining access to critical research is relevant for the agrifood community considering the current, global food crisis (Laborde and Glover, 2022). For instance, recent research of over 1.2 million children in 44 low-and middle-income countries suggests that experiencing the current crisis of food inflation increases both the risks of stunting and wasting in children under 5, including infants, as well as decreased diet quality for older children (Headey and Ruel, 2022). Greater visibility of critical agrifood research, complemented with computation tools to extract and classify "what works" and major gaps in the evidence base is urgently needed to help policymakers implement relevant policies that may mitigate disastrous consequences, especially for vulnerable populations.

5. Conclusion

Using machine-learning to analyze and quantify data gaps in agricultural research allows for greater understanding of the degree to which data and analyses are capturing systematic interactions. These approaches are current unavailable through other means, including expensive subscription databases. This approach to define important concepts like interventions can be especially useful in disciplines like agriculture and food systems, where well-coordinated, standardized evidence synthesis is lacking. Machine learning approaches enable us to perform close readings of a large, representative dataset and provide descriptive details that can be used to inform research agendas and prioritization. Studies like this are necessarily limited in the observations and analysis based on what we can glean from summary data, given that full-text analysis of more than one million papers requires extensive processing time. In this study, the capture mentions of interventions and their outcomes presents a useful "birds-eye view" for future interrogations of the data, but both access and additional evaluation of the underlying studies is needed to support whether the identified interventions and outcomes are consistent with the findings of each study. Still, such approaches allow opportunities to track research over time to create a global monitoring and evaluation framework.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: CAB Direct, GitHub.

Author contributions

JP oversaw study design, data analysis and methodology, and manuscript development. MI provided coding and computation support. LL contributed to data review and manuscript development. All authors contributed to the article and approved the submitted version.

Funding

This research was commissioned by the Commission for Sustainable Agriculture Intensification (CoSAI) and supported by funders contributing to the CGIAR Trust Fund.

Acknowledgments

We thank Mary O'Connor, Cristina Ashby, Martin Parr, and Andy Robinson of CABI for early review of previous versions of this manuscript and for providing access to the dataset. Thank you to Julia Compton for engaging and thoughtful questions and relevant feedback throughout the study design and analysis. We acknowledge and appreciate the role of COSAI advisory board and their feedback and support on early analysis.

Conflict of interest

MI was employed by EPAM Systems, Minsk, Belarus.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Tufan, H., Cichy, K., et al. (2020). A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nat. Plants* 6, 1231–1241. doi: 10.1038/s41477-020-00783-z

AGROVOC: AGROVOC Multilingual Thesaurus (n.d.). Available online at: https://www.fao.org/agrovoc/ (accessed July 31, 2022).

Amarante, V., Burger, R., Chelwa, G., Cockburn, J., Kassouf, A., McKay, A., et al. (2021).Underrepresentation of developing country researchers in development research. *Appl. Econ. Lett.* 1–6. doi: 10.1080/13504851.2021.1965528

Baltenweck, I., Cherney, D., Duncan, A., Eldermire, E., Lwoga, E. T., Labarta, R., et al. (2020). A scoping review of feed interventions and livelihoods of small-scale livestock keepers. *Nat. Plants* 6, 1242–1249. doi: 10.1038/s41477-020-00786-w

Barrett, C. B., Benton, T. G., Cooper, K. A., Fanzo, J., Gandhi, R., Herrero, M., et al. (2020). Bundling innovations to transform agri-food systems. *Nat. Sustain.* 12, 974–976. doi: 10.1038/s41893-020-00661-8

Beltagy, I., Lo, K., and Cohan, A. (2019). *SciBERT: A Pretrained Language Model for Scientific Text*. ArXiv:1903, 10676. [Cs]. http://arxiv.org/abs/1903.10676

Bizikova, L., Nkonya, E., Minah, M., Hanisch, M., Turaga, R. M. R., Speranza, C. I., et al. (2020). A scoping review of the contributions of farmers' organizations to smallholder agriculture. *Nat. Food* 1, 620–630. doi: 10.1038/s43016-020-00164-x

Bornmann, L., Haunschild, R., and Mutz, R. (2021). Growth rates of modern science: a latent piecewise growth curve approach to model publication numbers from established and new literature databases. *Hum. Soc. Sci. Commun.* 8, 1. doi: 10.1057/s41599-021-00903-w

Bornmann, L., and Mutz, R. (2015). Growth rates of modern science: a bibliometric analysis based on the number of publications and cited references. *J. Assoc. Inf. Sci. Technol.* 66, 2215–2222. doi: 10.1002/asi.23329

Callaghan, M., Schleussner, C.-F., Nath, S., Lejeune, Q., Knutson, T. R., Reichstein, M., et al. (2021). Machine-learning-based evidence and attribution mapping of 100, 000 climate impact studies. *Nat. Climate Change* 11, 1–7. doi: 10.1038/s41558-021-0 1168-6

Davis, B., Lipper, L., and Winters, P. (2022). Do not transform food systems on the backs of the rural poor. *Food Sec.* 14, 729–740. doi: 10.1007/s12571-021-01214-3

Devlin, J., Chang, M.-W., and Lee, K. (2018). *BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding*. ArXiv:1810, 04805. [Cs]. http://arxiv.org/abs/1810.04805

FAO. (2022a). *AGROVOC Multilingual Thesaurus*. Available online at: https://agrovoc.fao.org/browse/agrovoc/en/ (accessed July 31, 2022).

FAO. (2022b). *The State of Food and Agriculture 2022: Leveraging Agricultural Automation for Transforming Agrifood Systems*. Rome: FAO.

Fuso Nerini, F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., et al. (2018). Mapping synergies and trade-offs between energy and the sustainable development goals. *Nat. Energy* 3, 10–15. doi: 10.1038/s41560-017-0036-5

Garbaro, A., Carneiro, B., Charpenteir, A., Cerulli, G., Porciello, J., Ivanina, M., et al. (2020). *Leveraging Artificial Intelligence and Big Data for IFAD* 2, 0. Available online at: https://www.ifad.org/documents/38714170/42863493/athena.pdf/68906a2a-afde-7f9c-02b7-46822770611b (accessed July 31, 2022).

Gil, Y., Greaves, M., and Hendler, J. (2014). Amplify scientific discovery with artificial intelligence. *Science* 346, 171–172. doi: 10.1126/science.1259439

Headey, D. D., and Ruel, M. T. (2022). *Food Inflation and Child Undernutrition in Low and Middle Income Countries*. Washington, DC: International Food Policy Research Institute (IFPRI). doi: 10.2499/p15738coll2.136457

Jardine, B. (2021). *Case Study from USAID's Center for Water Security, Sanitation, and Hygiene*. Research Technical Assistance Center (December 29 2021). Available online at: https://www.rtachesn.org/resources/machine-learning-for-programmatic-synthesis/ (accessed July 31 2022).

Kennedy, G., Stoian, D., Hunter, D., Kikulwe, E., Termote, C., Burlingame, B., et al. (2017). "Food biodiversity for healthy, diverse diets," in *Bioversity International. Mainstreaming Agrobiodiversity in Sustainable Food Systems: Scientific Foundations for an Agrobiodiversity Index* (Rome, Italy: Bioversity International). p. 23–52.

Kroll, C., Warchold, A., and Pradhan, P. (2019). Sustainable development goals (SDGs): are we successful in turning trade-offs into synergies? *Palgrave Commun.* 5, 1–11. doi: 10.1057/s41599-019-0335-5

Laborde, D., and Glover, J. (2022). *No End in Sight Yet for the Global Food Price Crisis*. IFPRI: International Food Policy Research Institute. Available online at: https://www.ifpri.org/blog/no-end-sight-yet-global-food-price-crisis (accessed December 21, 2022).

Laborde, D., Porciello, J., Smaller, C., and Murphy, S. (2020). *Ceres2030: Sustainable Solutions to End Hunger Summary Report* [Report]. Ceres2030. Available online at: https://ecommons.cornell.edu/handle/1813/72799 (accessed July 31, 2022).

Laderchi, C., Kanbur, R., and Winters, P. (2022). *Inclusion as a Key Goal in the Transformation of Food Systems*. Food Systems Economic Commission Blog. Available online at: https://www.foodsystemeconomics.org/post/inclusion-as-a-key-goal-in-the-transformation-of-food-systems (accessed march 3, 2022).

Lipper, L., DeFries, R., and Bizikova, L. (2020). Shedding light on the evidence blind spots confounding the multiple objectives of SDG 2. *Nat. Plants* 6, 1203–1210. doi: 10.1038/s41477-020-00792-y

Liverpool-Tasie, L. S. O., Wineman, A., Young, S., Tambo, J., Vargas, C., Reardon, T., et al. (2020). A scoping review of market links between value chain actors and small-scale producers in developing regions. *Nat. Sustain.* 3, 10. doi: 10.1038/s41893-020-00621-2

Lowder, S. K., Sánchez, M. V., and Bertini, R. (2021). Which farms feed the world and has farmland become more concentrated? *World Develop.* 142, 105455. doi: 10.1016/j.worlddev.2021.105455

Luoma, J., and Pyysalo, S. (2020). *Exploring Cross-sentence Contexts for Named Entity Recognition with BERT*. (arXiv:2006, 01563). doi: 10.18653/v1/2020.coling-main.78

Nature (2020a). *Nature Portfolio: Sustainable Solutions to End Hunger*. Available online at: https://www.nature.com/collections/dhiggjeagd (accessed July 31, 2022).

Nature (2020b). Ending hunger: science must stop neglecting smallholder farmers. *Nature* 586, 336. doi: 10.1038/d41586-020-02849-6

Nordhagen, S. (2021). *Gender Equity and Reduction of Post-Harvest Losses in Agricultural Value Chains*. Global Alliance for Improved Nutrition Working Paper #20. Geneva, Switzerland. doi: 10.36072/wp.20

OECD. (2019). *Digital Opportunities for Better Agricultural Policies*. Paris: OECD. doi: 10.1787/571a0812-en

Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., et al. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nat. Sustain.* 3, 809–820. doi: 10.1038/s41893-020-00617-y

Porciello, J., Coggins, S., and Mabaya, E. (2022). Digital agriculture services in low- and middle-income countries: a systematic scoping review. *Global Food Security* 34, 100640. doi: 10.1016/j.gfs.2022.100640

Porciello, J., and Ivanina, M. (2021). *The Role of Machine Learning in Programmatic Assessment: A Case Study from USAID's Center for Water Security, Sanitation, and Hygiene*. Research Technical Assistance Center. Available online at: https://www.rtachesn.org/resources/machine-learning-for-programmatic-synthesis/ (accessed July 31, 2022).

Porciello, J., Ivanina, M., Islam, M., and Einarson, S. (2020). Accelerating evidence-informed decision-making for the Sustainable Development Goals using machine learning. *Nat. Machine Intell.* 2, 10. doi: 10.1038/s42256-020-00235-5

Rafols, I., Ciarli, T., and Chavarro, D. (2020). *Under-Reporting Research Relevant to Local Needs in the Global South*. Database biases in the representation of knowledge on rice. SocArXiv. doi: 10.31235/osf.io/3kf9d

Reardon, T., Lu, L., and Zilberman, D. (2019). Links among innovation, food system transformation, and technology adoption, with implications for food policy: overview of a special issue. *Food Policy* 83, 285–288. doi: 10.1016/j.foodpol.2017.10.003

Ricciardi, V., Wane, A., Sidhu, B. S., Godde, C., Solomon, D., McCullough, E., et al. (2020). A scoping review of research funding for small-scale farmers in water scarce regions. *Nat. Sustain.* 3, 836–844. doi: 10.1038/s41893-020-00623-0

Serraj, R., and Pingali, P. (2018). *Agriculture and Food Systems to 2050: Global Trends, Challenges and Opportunities (Vol. 2)*. Singapore: World Scientific. doi: 10.1142/11212

Sharma, Y., Agrawal, G., and Jain, P. (2017). "Vector representation of words for sentiment analysis using GloVe," in *2017 International Conference on Intelligent Communication and Computational Techniques (ICCT)*, p. 279–284. doi: 10.1109/INTELCCT.2017.8324059

Snilstveit, B., Vojtkova, M., Bhavsar, A., and Stevenson, J. (2016). Evidence and Gap Maps: a tool for promoting evidence informed policy and strategic research agendas. *J. Clin. Epidemiol.* 79, 120–129. doi: 10.1016/j.jclinepi.2016.05.015

Stathers, T., Holcroft, D., Kitinoja, L., Mvumi, B. M., English, A., Omotilewa, O., et al. (2020). A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. *Nat. Sustain.* 3, 821–835. doi: 10.1038/s41893-020-00622-1

Sumberg, J., and Hunt, S. (2019). Are African rural youth innovative? Claims, evidence and implications. *J. Rural Stud.* 69, 130–136. doi: 10.1016/j.jrurstud.2019.05.004

Teeken, B., Olaosebikan, O., Haleegoah, J., Oladejo, E., Madu, T., Bello, A., et al. (2018). Cassava trait preferences of men and women farmers in nigeria: implications for breeding. *Econ. Botany* 72, 263–277. doi: 10.1007/s12231-018-9421-7

Vincent, A., Huang, C., and Lal, T. (2022). *Mapping evidence to strengthen impact on resilience and food security. International Initiative for Impact Evaluation (July 21 2022)*. Available online at: https://www.3ieimpact.org/blogs/mapping-evidence-strengthen-impact-resilience-and-food-security (accessed July 31, 2022).

Wagner, C. S., Cai, X., and Zhang, Y. (2022). One-year in: COVID-19 research at the international level in CORD-19 data. *PLoS ONE* 17, e0261624. doi: 10.1371/journal.pone.0261624

Wang, L. L., Lo, K., Chandrasekhar, Y., Reas, R., Yang, J., Burdick, D., et al. (2020). *CORD-19: The COVID-19 Open Research Dataset* (arXiv:2004, 10706). arXiv. http://arxiv.org/abs/2004.10706

Woodhill, J., Hasnain, S., and Griffith, A. (2020). *What Future for Small-Scale Farmers?* Oxford: Environmental Change Institute.

frontiers | Frontiers in Sustainable Food Systems

TYPE Hypothesis and Theory
PUBLISHED 04 April 2023
DOI 10.3389/fsufs.2023.1053152

Check for updates

OPEN ACCESS

EDITED BY
P. V. Vara Prasad,
Kansas State University, United States

REVIEWED BY
Netra B. Chhetri,
Arizona State University, United States
Araya Berhe,
Kansas State University, United States

*CORRESPONDENCE
Richard D. Kohl
✉ richardkohl@strategyandscale.com

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 25 September 2022
ACCEPTED 13 March 2023
PUBLISHED 04 April 2023

CITATION
Kohl RD (2023) Key factors for advancing innovations to scale: Evidence from multiple country case studies of agricultural innovations. *Front. Sustain. Food Syst.* 7:1053152.
doi: 10.3389/fsufs.2023.1053152

Key factors for advancing innovations to scale: Evidence from multiple country case studies of agricultural innovations

Richard D. Kohl*

Strategy and Scale LLC, Beaverton, OR, United States

Innovation pathways can be defined as a sequence of innovation, going to scale, and implementation at sustainable scale, where innovation is a new product, service or systems change not previously introduced in a specific context. They can take the form of new products or services, institutions, or systems change. Such pathways can play a lead role in transforming agri-food systems in low- and middle-income countries. To get us to our global goals, these pathways have to lead to impact at a scale that matches the size of the challenge. Unfortunately, while there are many proposals in the published and gray literature for integrated, transformative approaches to innovation pathways, few have yet either gone to scale or been implemented sustainably at large scale. Here we assess whether there is evidence to support these proposals about how agricultural innovation pathways should be pursued. In this paper we identify from the literature and case studies 10 potentially key factors for advancing scaling along the innovation pathway: participation, inclusion, leadership, iteration, adaptation, the specific attributes of innovation design, funding models, implementation models, systems change, and partnerships. We test these factors against a collection of innovation and scaling case studies from Bangladesh, Brazil, India, Kenya, Senegal, Uganda, and Zambia. While the cases are somewhat limited in their quantitative measures of successful implementation at scale, the qualitative evidence presented in the cases confirms both the general importance of these factors in action and that their importance varies depending on the innovation and context. While confirmation of the importance of these factors is not surprising in itself, we also demonstrate their specific design and implementation (or absence) in different contexts, how each element contributes to success at large scale, and actionable examples to be applied in practice. The paper concludes that integrating these factors will likely require changes to traditional approaches to development, innovation and scaling in agri-food systems. Specifically advancing along an innovation pathway to large scale will require a commitment of greater resources over longer time horizons. In the absence of greater overall resources, this implies focusing on fewer innovations at each phase and a greater appetite for risk and failure in individual cases, suggesting adoption of a portfolio rather than a project approach in evaluating success. This may lead to more unsuccessful individual efforts, but those will be offset by a few transformative successes which will change the lives of hundreds of millions, if not billions.

KEYWORDS

innovation pathways, scaling, sustainable agricultural intensification, systems change, scaling up, case studies, agricultural innovation, bundling

1. Introduction

Innovation pathways are composed of a sequence of activities that start with basic innovations, continue with efforts to go to scale, and end with sustainable impact at large scale (see Figure 1 below).[1] Innovations are a new product, service or systems change not previously introduced in a specific context.[2] In recent years, however, the agri-food systems literature has seen mounting discussion on the poor performance of innovations in achieving their potential impact at scale, and sustainable agricultural intensification (SAI) in particular. This suggests that the study of what drives success, and failure, of innovations to advance along an innovation pathway is particularly timely.

While it is widely recognized that the innovation and particularly scaling parts of innovation pathways are flawed, diverse authors use different language to describe both the problem and the solutions. They may locate the problem in the innovation process itself, scaling, the way those two are sequenced and integrated, or how important aspects that contribute to success are missing or inadequate, e.g., the role of systems change or participation. Their proposed solutions are often similar in substance but presented in different terms: sustainable systems change at scale (Woltering et al., 2019); adaptive scaling (Minh et al., 2021); scaling principles (Kohl and Linn, 2021); sustainable intensification (Pretty et al., 2011); end-to-end innovation (Koerner and Duda, 2021); scaling science (Shilombenia et al., 2019); bundling innovations (Barrett et al., 2020); agro-ecology; agricultural innovation systems; social-ecological systems; or political ecology (all covered in Foran et al., 2014).

There are three reasons why this discussion is happening so broadly right now. First and foremost, there is a consensus that innovation can play a lead role in transforming agri-food systems in low- and middle-income countries (see, for example, World Bank, 2019; Butler, 2021; Khan et al., 2021). Secondly, this belief has been accompanied by significantly increased investments in agri-food innovations following the food crisis of 2007–2008. These investments has been heavily influenced by the increased prominence of the technology sector in the global economy overall. There has been a particular focus on technology innovations as a way of circumventing the resource, institutional and governance challenges that have made achieving large-scale impact in low-resource settings challenging.

Lastly, it is generally acknowledged that if the current rate of progress toward the Sustainable Development Goals—particularly those that relate to agriculture, nutrition and food security—continues, those goals will not be met in most lower-income countries (see FAO, 2021). The same is true for addressing and reducing agri-food systems' contribution to climate change and achieving the Paris Agreement's objectives. This has created a global sense of urgency and recognition that existing approaches are not working. Given that vastly increased resources are not likely to be forthcoming to fill the gap, better approaches to innovation and scaling are needed that achieve much greater impact with existing resources. This implies either greater efficiency and effectiveness in the innovation and scaling process itself, or achieving economies of scale at scale. These are among several issues we address in this paper.

1.1. A new consensus on scaling innovations

The numerous reforms that authors have proposed in response have several claims in common:

- For innovation to be meaningful it should lead to sustainable change at *large scale*. Large scale needs to be defined relative to the size of the problem or the denominator: millions reached, while important for those people, is irrelevant if the problem affects and SDG goals involvebillions of people.
- This needs to occur through a combination of scaling of technological innovations in products or services and *systems changes and institutional innovations*. It is a rare case where scaling of an innovation occurs without systems change. At best, when scaling is defined in its narrowest sense of getting more end users to adopt an innovation, the innovation is likely to be limited impact in terms of sustainability or addressing other issues besides productivity and food security, such as nutrition, health, income inequality, gender equity, and environmental sustainability. It may also have unintended negative consequences, especially if complexity is ignored.
- The need for *systems changes and institutional innovations*, either as stand-alone changes, or as accompanying traditional innovations in products and services, implies that the traditional diffusion of innovation pathway and success criteria, e.g., innovative adopters, early adopters, early majority, etc. is only relevant to some types of innovations and innovation pathways. More importantly, the diffusion of innovation approach doesn't take into account the need for systems change, the role of context or differences between scaling of tangible vs. intangible (components of) innovations e.g., products vs. behavior change. If anything by focusing on the number of adopters encourages neglect of both the need for systems change and the need to put in place institutional, individual behavioral and changes in community and social norms. These can be invaluable for large scale impact on their own or so as to facilitate spontaneous growth in the number

1 It is common in the literature to see innovation and scaling as anywhere from a three to six phase process. For example, the International Development Innovation Alliance (IDIA), a consortium of international development funders, uses six: (i) Ideation; (ii) Research and Development; (iii) Proof of Concept; (iv) Transition to Scale; (v) Scaling; and (vi) Sustainable Scale. For the purposes of this article, three phases suffice; our Innovation phase contains IDIA phases 1–3, Going to Scale contains IDIA phases 4 and 5, and Sustainable Implementation is equivalent to the IDIA phase 6. See International Development Innovation Alliance (IDIA) (2017).

2 This definition of innovation is also taken from the International Development Innovation Alliance (IDIA), which defines innovation as "a solution new to a given context with the transformative ability to increase impact". See International Development Innovation Alliance (IDIA).

FIGURE 1
Three phase approach to scaling.

of adopters of products and services as well as sustainability. It also neglects necessary tradeoffs between numbers, impact, sustainability, equity and other factors like participation (e.g., LaMorte, 2022).

- Rather than scale in the narrow sense of numbers of adopters, the goal needs to be *optimal scale* to sustain systems change, recognizing that there are necessary trade-offs between multi-dimensional impact, scale, sustainability and equity.
- Last and most importantly, the *innovation process itself* needs to integrate considerations of scaling, systems change and institutional innovation. From the very start of the pathway, innovation processes need to "treat scaling as a systemic change process" (Minh et al., 2021).

An implication of the consensus is that the development of an innovation needs to start with analyzing systems, clearly identifying the problem(s) to be addressed and setting a vision and clear goals as to what sustainable large-scale change might look like, especially in terms of resources and implementation or delivery capacity (Hubeau et al., 2017; Klerkx and Begemann, 2020). The various phases of problem definition, innovation, scaling and institutionalization need to be both adaptive and iterative *and* participatory and inclusive so as to be effective in achieving impact, responding to demand and local circumstances, and accomplishing the necessary local buy-in and ownership (Table 1).

This requires specific kinds of leadership, well-resourced intermediary actors who facilitate scaling—i.e., helping innovations cross the "valley of death" between pilots and proof-of-concept and institutionalization, champions, and some form of multi-stakeholder consultative process. At the same time, it is necessary to recognize that increased attention to complexity, systems change, participation and equity can greatly increase the time, effort and resources required to do all of this and needs to find a reasonable balance (see Seelos, 2020; Kohl and Linn, 2021; Seelos et al., 2021; Starr, 2021).

2. Materials and methods

Unfortunately, few proposals for an integrated broad, inclusive, transformative systemic approach have actually been implemented at large scale. They have certainly not been tested with multiple types of innovations in different contexts. Even if such applied research is under way, scaling and systems change is commonly acknowledged to take 10–15 years. It is still too early to assess whether (or under what circumstances) such research can shed light on the claims and methodologies.

We have taken at least a first step in terms of assessing whether there is evidence to support proposals about how agricultural innovation pathways should be pursued, and what those hypotheses look like beyond high-level generalizations. We started by looking at the recent literature that proposes principles and approaches to achieving large-scale SAI in agri-food systems. While most of these sources propose comprehensive approaches, we disaggregated these into individual components and drew out six testable hypotheses (Table 2):

1. Innovation pathways must be participatory and inclusive.
2. Leaders, intermediaries and champions are key to innovation pathways.[3]
3. Innovation pathways should be iterative, adaptive and flexible.
4. Innovations should have characteristics that facilitate progress along innovation pathways and achieving large-scale SAI.
5. Innovations must be packaged with viable funding and implementation models and bundled with systems change.[4]
6. Partnerships are critical for innovation, scaling and systems change.

While some of these hypotheses are not new, this study and the underlying case studies upon which it draws, adds value by describing how these principles were, or were not, applied in practice, and what the consequences were. This institutional detail will provide the reader with some examples to follow in implementing these principles, should they so choose.

We then looked to case studies of innovation pathways, trajectories, scaling and other attempts at achieving large-scale SAI (Table 3). Our first source of cases was three country studies—from Brazil (Chiodi Bachion et al., 2022), India (Khandelwal et al., 2022) and Kenya (Mati et al., 2022)—commissioned by the Commission on Sustainable Agriculture Intensification (CoSAI), each of which contained three to four individual cases. All of these cases were

3 These are defined under Hypothesis 2 in Results. Intermediaries fulfill brokering and scaling roles where innovators might lack the skills, capacity, resources, motivation or incentives. Champions are people in a position to influence the behavior of others in the relevant sphere.

4 Packaging and bundling are defined under Hypothesis 5. These are used, with overlapping meanings, in referring to elements of an innovation beyond a single core technology or institutional characteristic. We use packaging to refer to funding and implementation models and bundling to refer to systems change. Other literature may use the same words for combinations of technical innovations, which is not the intended meaning in this paper.

TABLE 1 Changes needed in three phases of innovation pathways to improve outcomes.

Innovation process itself	Going to scale	Sustainable implementation at scale
• Integrate scale and systems change into the innovation process itself	• Accompanied by systems change to allow for sustainability and maximize impact	• Must reach LARGE scale, signifincan share of the problem
• Start with defining large scale goals and a scaling strategy	• Recognize that scaling is a dynamic and emergent process	• Make trade-offis between impact, scale, sustainability & equity i.e. optimal scale
• Leadership and champions are essential in all three phases		
• Partnerships are important in all three phases, and importance increases from Phase I to II to III		
• Participation, Inclusion and creating local buyin and ownership is necessary in all three phases		
• Expect that scaling is a funnel, with a steadily decreasing percentage of innovations achieving Phase III. Requires greater tolerance for risk in innovation; higher risk should yield higher returns on aggregate in terms of scale		
• Analyze with systems at large scale, align with constraints	• Follows an adaptive, iterative, participatory and inclusive strategy	• Achieve economies of scale
• Align with known criteria that facilitate scaling and sustainability	• Is inherently political, requires achieving buy-in and ownership	• Sustainabiliy involves financing and other resources, implementation capacity, and political
	• Intermediaries are necessary with scaling-specific skills and resources	• Sustainable financing implies a viable business model or funding aligned with fiscal resources

identified by the study authors based on several criteria developed by COSIA, perhaps which the most important that there was clear evidence of ongoing adoption and utilization of innovations at large scale, i.e., sustainability. These case studies have strengths and weaknesses: they provide valuable insights and detailed stories and examples of how these factors apply to innovation pathways. While the study authors did attempt to assess the role of local context and conditions, since all of these cases only occurred in one country, this does not allow for any conclusions about cross-country (or context) replicability of the approaches used (in one of the Brazilian cases, the approach was scaled up to both other sub-sectors in agriculture and to other Latin American countries). That said, the study authors all did comment that relatively strong public sector capacity did likely play an important role in Brazil and India, and strength of Kenya's agricultural market systems and institutions, at least as compared to the rest of East Africa, were similarly important.

At the same time, they are largely qualitative in nature. The quantitative data they contain on issues like costs, unit costs, impact on productivity or other outcomes, the scale reached and how that compares with potential scale, is often missing or at best uneven.[5] Even guestimates of scale reached would suggest that in terms of direct participants, it is likely that in none of these cases did the innovation reach a scale of more than 15% of total potential, and in most cases probably <5%. As in traditional diffusion of innovation frameworks "innovators" are the first 2.5% of adopters, and "early adopters" are the next 13.5%, these innovations at the very best all innovators and early adopters, let alone an early majority. However such figures can be misleading; the lack of accurate data is further complicated by the fact that potential adopters who did not themselves participate in the program may have benefited because they learned from the example of their neighbor.[6] Measuring scale is particularly challenging when an innovation has multiple components; neighbors may have adopted some parts of an innovation package but not others. A similar question arise for both direct and indirect adopters regarding sustainability; for how many years or seasons must an adopter continue to practice or implement an innovation for it be counted as "adopted"? In the absence of truly thorough, ongoing evaluations, we have no way of knowing the extent of spontaneous or indirect adoption and scaling, whether the whole package or individual components are adopted, and for what period.[7]

Our second source was a set of five case studies commissioned by the United States Agency for International Development (USAID) Bureau of Resilience and Food Security, similarly seeking to identify drivers of successful scaling of agricultural innovations (Foy and Wafula, 2016; Kohl, 2016a,b,c; Foy, 2017). Because these

5 This is explained by the fact that these studies deliberately looked at scaling through public or private pathways but not development projects funded by international donors; the latter often do much more extensive monitoring and evaluation than the public sector. Private data is often proprietary and either completely unavailable to researchers as well as, in many cases, require gathering it from multiple enterprises, e.g., solar irrigation pumps in Kenya.

6 For example, the One Land and Two Waters model in Brazil was replicated by municipal governments, but those figures were never counted in national totals.

7 For example, Balde Cheio in Brazil assisted dairy farmers in improving production. It contained six *categories* of intervention: fodder production; production systems; farm management; genetics; agronomics; and administration issues. Each category in turn contained multiple activities and options. There are roughly one million dairy farms in Brazil. Balde Cheio began in 2003 and continues to this day, working in 21 of Brazil's 26 states. In any given year the program was working with between 500 and over 4,000 farmers, with 3–4,000 in the peak years of 2009–2013 and 1,626 farms in 2020, the most recent year for which data is available. As the annual totals include farms from previous and future years, there is no accurate estimate in the study of the total number of farmers reached; a generous guestimate would put the total number of farmers *participating* at a maximum of 40,000, or four percent of the total dairy farms. However if 3–4–5 or more farms learned from participants, the impact could have affected 12%–20% of dairy farms or more.

TABLE 2 Hypotheses considered and tested.

Hypothesis	Evidence available from cases	Evidence supports/ contradicts	Decision
Innovation should follow a planned, explicit, well-thought-out and **deliberate process** based on identification of the problem (**mission driven**), **a solution** and **a clear theory of change**	No	Not Relevant	Not assessed
Innovation pathways should **begin with the end in mind**	Some	Unclear	Not assessed
Innovation pathways should specify **what** is being scaled or effecting systems change, a **vision** of scale/impact, and a **clear strategy and pathway** to achieve them	Little	Unclear	Not assessed
Innovation pathways must be **participatory and inclusive** from the beginning, especially of end users, in terms of co-creation of innovations and/or systems changes, and identifying a vision and goals for large-scale change	Yes	Supports	Assessed (#1)
Leaders, intermediaries and champions are critical to successfully achieving sustainable impact at large scale	Some	Supports	Assessed (#2)
Innovation pathways should be **iterative, adaptive and flexible** using rapid testing and failing fast apply a cycle of experimentation, learning and strategic adjustments	Yes	Supports	Assessed (#3)
Innovations should have **characteristics aligned with criteria that facilitate scalability,** especially the needs, context and constraints faced by end users	Yes	Supports	Assessed (#4)
Institutional and individual **incentives** of all stakeholders, from end users to private value chain actors and the public sector, **must be aligned** with innovation and scaling goals	Some	Supports	Not assessed
Viable financial and/or business models and **implementation mechanisms** are necessary; product and service innovations need to be packaged with financing and delivery mechanisms. **Who** will play key roles of Payer and Doer (operationalizing or implementing) needs to be specified	Yes	Supports	Combined into one hypothesis (#5)
Innovations must be **bundled** with analysis and changes in markets, value chains and policy enabling environment institutions and systems	Yes	Supports	
Analyze systems taking into account complexity and unintended consequences. Identify **systemic opportunities, constraints and risks**; plan to align with them or address them through system change along the scaling pathway	Some	Supports	
Partnerships are critical to innovation pathways, both for innovation, systems change and scaling; bringing multiple perspectives to the table; mobilizing resources beyond those of one actor; and aligning incentives and political support	Yes	Supports	Assessed (#6)
Social capital needs to be leveraged and/or created where necessary e.g., farmers' organizations, women's organizations	Yes	Supports	Not assessed
Diverse types of **evidence** are necessary for successful scaling and innovation well beyond standard proof of concept or proof of impact	Some	Mixed	Not assessed
Innovation and scaling affect, and are affected, by **considerations of power, equity and other ethics**. These should be considered in addition to impact on goals like productivity, income and food security	No	Not Relevant	Not assessed

studies cover only one innovation or group of related innovateons and interventions, were both of USAID projects and financed by USAID projects, they have much greater depth. Nonetheless, even though the initial intention was to include in these studies estimates of scale achieved, how that compared to normal diffusion of innovation curves, and what that implied for tipping points, they were not able to achieve that goal. The USAID projects themselves, despite a huge investment in monitoring and evaluation, did not collect the necessary data to provide even rough estimates of scale and tipping points. For the sake of brevity, for each hypothesis tested below, we give examples from only those cases which seem to be have the most significant evidence.

Our chosen case studies are not examples of perfect success in taking innovation pathways to scale. While some have reached 5 or 10% of potential users, others have only scaled to much smaller levels. Nonetheless all reached or affected thousands of people or farms and in many cases this was in the tens or hundreds of thousands. Indeed, an important finding of our review is that most scaling efforts lack either a vision or measure of success,[8] rather they have tended to make it up as they go along, with reaching "more" people in places being the operative phrase in those cases where there were deliberate scaling efforts and strategies. While the majority of cases had scaling strategies in some operational sense, most were not based on any explicit set of principles, factors or a strategic approach in advancing innovations along scaling pathways (the Bangladesh and Senegal USAID cases did embody such factors). Despite these considerations, we believe that the

8 In none of the CoSAI studies and only two of the five USAID studies did the scaling efforts have explicit vision or goals for success; the Brazilian government did consider the three public sector cases as successes though it is not clear what the criteria for that assessment was.

TABLE 3 Summary of cases.

Case	Innovating organization	Innovation package type and description
Balde Cheio—Full Bucket *Brazil 1998–*	Brazil Agricultural Research Corporation (Embrapa)	**Innovative extension approach.** Farmer-oriented innovation program with an experimental and incremental approach to improve dairy productivity by training local rural extension technicians, using farms as schools
One Land Two Waters (P1+2) *Brazil 2007–*	Articulation in the Semiarid Region (ASA), One Million Cisterns (AP1MC), Ministry of Social Development	**Technology, social capital.** Improved water access through harvesting and storage for farming
Integrated Livestock, Crops and Forestry *Brazil 2008–*	Embrapa, ILPF Network	**Integrated technology.** An integrated approach for livestock and crop production (ILP), in some cases also adding forests (ILPF)
Aqua Digital Irrigation Monitoring System *Brazil 2014–*	Agrosmart	**Technology, extension.** Digital monitoring irrigation system with a platform to support farmer decisions
Andhra Pradesh Natural Farming *India 2016–*	Rythu Sadhikara Samstha (RySS) (farmers' empowerment association)	**Integrated technology.** Distributed innovation to decrease or eliminate agrochemical use and adopt zero budget natural farming
Safe Harvest *India 2009–*	Safe Harvest (triple bottom line private company)	**Production, market links.** A farm-to-kitchen model for certified pesticide-free food, supporting farmers
Trustea *India 2013–*	Consortium of private tea processors and sellers with support from NGOs	**Production, standards, market links.** Verifiable standards for sustainable tea production, along with extension and capacity support for farmers
Water Harvesting *Kenya 2009–*	External innovation promoted by NGOs and county governments	**Technology.** Water storage ponds for irrigation
Solar Powered Irrigation *Kenya 2005–2021*	External innovation with multiple private sector variations	**Technology, finance.** Solar powered pumps and panels, sometimes combined in kits, and some innovative financing.
Upper Tana–Nairobi Water Fund *Kenya 2012–2020*	Multistakeholder: county governments, private sector, NGOs (Nature Conservancy)	**Technology, finance.** Partnership and coordination mechanism between water and land users to promote water conservation and management through blended financing
Sahel Rice *Senegal 2009–2015*	AfricaRice, Projet Croissance Economique (PCE)	**Technology.** Interventions to realize the production potential of improved varieties of rice that were first introduced and scaled in the 1990s
Purdue Improved Crop Storage Bags *Kenya 2013–2018*	Purdue University	**Technology.** Large hermetically sealed bags for post-harvest storage to reduce losses due to moisture, mold and rot
Kuroiler Chickens *Uganda 2010–2017*	Arizona State University, Ugandan National Animal Genetic Resource Center	**Technology.** A hybrid chicken breed introduced from India, with much higher meat and egg production in a shorter time period than local chickens
Drought Tolerant Maize for Africa/Hybrid Maize *Zambia 2006–2015*	International Maize and Wheat Improvement Center (CIMMYT), International Institute of Tropical Agriculture (IITA), African national research agencies	**Technology.** Over 200 hybrid and open pollinated maize varieties that are able to tolerate some drought conditions during certain periods of the growing season
Mechanization Initiative *Bangladesh 2013–2018*	iDE, CIMMYT, IRI; scaling by CIMMYT's Cereal Systems Initiative for South Asia (CSISA) in partnership with private machinery producers/importers	**Technology.** Innovations to improve rice production or allow for greater uptake of maize and wheat production through irrigation and cost, time and labor savings: a reaper, improved irrigation pump, planter/tiller attachment for two-wheeled tractors and a bed planter, which improved on existing machinery or replaced hand labor

progress and scale achieved, as well as the problems observed, combined to yield important insights and provide sufficient support for the conclusions drawn to be considered seriously.

The principles by which innovation pathways should be followed and connected with systems change—even those widely assumed to be important and promoted at length—are still rarely deployed to an adequate extent in any conscious, explicit or strategic sense at that was true in these cases as well, with the noted exceptions of Bangladesh and Senegal. Similarly, there is little empirical evidence on whether these fatores are in fact applicable to scaling of innovations in different contexts. Certainly factors like the relatively strong state capacity, leadership and fiscal resources in India and Brazil is less present in low-income countries in Sub-Saharan Africa or elsewhere, and that was noted in those studies. The testing of hypotheses in this paper is only a first step in filling those gaps and projects and action research to test the replicability of these factors in different contexts, or when explicitly serving as the basis for innovation and scaling strategy, is sorely needed.

Notwithstanding all of these caveats, the case study analysis strongly suggests that the six hypotheses are indeed important to innovations moving successfully along innovation pathways and achieving large-scale SAI. While this is not surprising in itself, our intention below is to investigate their specific design and implementation (or absence) in the cases, providing examples and counter-examples of practice that contribute to success, to derive more useful conclusions about how each element contributes.

3. Results

3.1. Support to Hypothesis 1: Innovation pathways must be participatory and inclusive

Participatory agricultural research, and more broadly participatory rural development, have a literature going back to at least the early 1980s. In each decade since, a review of the literature reveals advocates calling for greater participation by end users in agricultural research for normative, ethical and instrumental reasons. Focusing on participation as a means to other ends, advocates argue that local stakeholders need to be incorporated because they have a better understanding of local needs, demands, contexts, conditions and existing practices, especially when natural resource management is at issue. At the same time, participation can be time-consuming, costly, and opposed by technical experts. While widely acknowledged by leading funders of development as important, the extent to which this is empirically true, how it is practiced in scaling in particular, and the extent to which it actually makes a difference in ultimate outcomes, is still the subject of debate.

Application of participation to agricultural innovation pathways has at a minimum meant that farmers are consulted in the innovation process, and more and more are part of learning alliances and the identification and/or co-creation of promising innovations and their testing.[9] They also participate in analysis of the larger systems as the foundation for subsequent decisions about what is to be scaled or about systems changes.

Participation in innovation and scaling can vary widely from consultation to being informed to having real power in the design of innovations and scaling strategies, as well the implementation of those strategies. This variety was very much present in the cases reviewed for this study. The extent to which our cases seemed to support or contradict this hypothesis, alongside the other hypotheses to follow, is illustrated in Table 4.

P1 + 2 (Brazil) (Chiodi Bachion et al., 2022) was the most participatory of the Brazilian public sector pathway cases, a social technology program driven by the mobilization and organization of family farmers, rural communities, the social movement ASA[10] and other civil society actors. Its express goal was "democratizing, accessing and building technological solutions that advance social inclusion". Chiodi Bachion et al. (2022) characterize the choice of technologies as a "bottom-up innovation process" that started with a number of technologies and the knowledge of local people that were then assessed and selectively chosen by public sector technicians based on their costs, longevity and benefits. The process was at least action-oriented for individual farmers, and social organizations had a clear say in decision making. Social mobilization and collective training were key parts of scaling. As a result of inclusion, innovations were highly relevant to the specific needs of people living in the semiarid region, especially increasing their resilience to food insecurity and climate change. Similarly, because of the participatory training, families understood the importance of maintaining cisterns for food security and income generation, so sustainability was a hallmark of the program.

Aqua Digital Monitoring Irrigation System (Brazil) (Chiodi Bachion et al., 2022) saw the start-up Agrosmart include early adopters—mostly large farmers—in the initial demonstration of results and subsequent adjustments. These participants conducted pilot tests and provided feedback to improve the monitoring system and its usability. In scaling up, Agrosmart retained an unofficial committee of test customers for each of their products and kept weekly contact with these farmers, who were rewarded with the opportunity to customize the service to their needs. As a result, Agrosmart's products were aligned with the specific needs and requirements of its customers.

Andhra Pradesh Natural Farming (India) (Khandelwal et al., 2022) combined technological chemical-free practices and traditional methods for increasing productivity and resilience with social technologies such as community mobilization and empowerment. For this the program used a distributed innovation approach in which "farmers become experimenters and innovators to find solutions suitable to their context" (Khandelwal et al., 2022) and a farmer-to-farmer extension model to diffuse and scale the innovations to more farmers. It was successful in lowering input quantities and therefore costs, and had clear environmental benefits. The combination of a farmer-driven design and the inclusive farmer-to-farmer diffusion approach increased the willingness of farmers to try the innovation, allowed for scaling to farmers not directly participating in training, vastly increasing its coverage.

Sahel Rice (Senegal) (Kohl, 2016c) featured the greatest involvement of end users among the five USAID cases. All of the implementation was done working closely with farmers' organizations, in this case irrigation user groups. The development of institutional innovations such as an innovative financing mechanism was done in close consultation with

9 See World Bank (2012, p. 440): "Considerable progress has been achieved in giving farmers access to innovation resources and in building their capacity." This publication also emphasizes the growing role of innovation funds available to local farmers or farmer organizations.

10 ASA was a full partner in goals, strategies and large-scale implementation. ASA is a network of more than 3,000 different types of civil society organizations, such as rural workers' unions, farmers' associations, cooperatives and NGOs.

TABLE 4 Support to hypotheses 1–6.

Case	Support to hypothesis						
	1	2	3	4	5-P	5-B	6
Balde Cheio, Brazil	Some support	Strong support	Strong support	Some support	Unclear support	Unclear support	Strong support
P1+2, Brazil	Strong support	Some support	Some support	Some support	Strong support	Some support	Strong support
ILPF, Brazil	Some support	Some support	Strong support	Some support	Counter-example	Strong support	Some support
Aqua Digital Monitoring Irrigation System, Brazil	Strong support	Some support	Some support	Some support	Strong support	Unclear support	Unclear support
Andhra Pradesh Natural Farming, India	Strong support	Strong support	Strong support	Strong support	Some support	Unclear support	Some support
Safe Harvest, India	Some support	Some support	No significant evidence	Some support	Some support	Unclear support	Some support
Trustea, India	Contradicts	Some support	No significant evidence	Some support	Some support	Unclear support	Strong support
Water Harvesting, Kenya	Some support	Unclear support	No significant evidence	Strong support	Counter-example	Unclear support	Some support
Solar Powered Irrigation, Kenya	No significant evidence	Unclear support	Some support	Strong support	Some support	Unclear support	Unclear support
Upper Tana–Nairobi Water Fund, Kenya	Some support	Some support	Some support	No significant evidence	Strong support	Unclear support	Strong support
Sahel Rice, Senegal	Strong support	Strong support	Strong support	Some support	Strong support	Strong support	Strong support
PICS Bags, Kenya	No significant evidence	Unclear support	No significant evidence	Strong support	Contradicts	Contradicts	No significant evidence
Kuroiler Chickens, Uganda	Counter-example	Strong support	Counter-example	Some support	Counter-example	Unclear support	Strong support
Drought Tolerant Maize for Africa/Hybrid Maize, Zambia	No significant evidence	Counter-example	No significant evidence	Counter-example	Strong support	Strong support	Strong support
Mechanization Initiative, Bangladesh	Counter-example	Some support	Strong support	Strong support	Strong support	Unclear support	Strong support

Hypothesis 5 is divided into sub-hypotheses on packaging (5-P) and bundling (5-B).

10.3389/fsufs.2023.1053152

farmers, rice millers, wholesale buyers and financial institutions. Farmers' organizations themselves also played the role of social entrepreneurs, developing and implementing solutions to obstacles, with USAID support and facilitation, within the rice value chain as they arose. The results of this inclusive approach was to ensure local ownership and particularly financial sustainability once donor investments ended, and to catalyze a virtuous spiral of farmers' organizations systematically addressing new challenges as scale increased.

Kuroiler Chickens (Uganda) is one telling counter-example where farmers were not involved to any degree in the initial selection and testing of technical innovations. According to Foy (2017) this proved problematic as changing from domestic breeds to Kuroilers required poultry farmers to adopt new chicken-rearing practices. At least initially, many farmers were either ignorant or misunderstood the changes required, or couldn't afford them; as a result some early adopters suffered heavy or complete losses. For example, farmers bred Kuroilers with domestic chickens, as they always had, yet as F1 hybrids the characteristics quickly disappeared in subsequent generations. In addition to the lack of inclusion of end users, the reach and resources of public extension systems were too limited to provide adequate support, meaning farmers had no one to help them deal with the problems. The **Mechanization Initiative (CSISA-MI[11] in Bangladesh)** (Kohl, 2016b) encountered a similar pitfall when four types of machines were initially imported to meet farmers' needs but they were not involved in the initial selection or testing of the machines. Project staff had to spend a few years retroactively modifying and adapting the machines using user-centered design principles, and only ended up with two of the four machines being ones that had long-term mass appeal to small farmers.

Trustea (India) (Khandelwal et al., 2022) seemed to treat farmers' organizations as passive recipients of technology packages delivered through technical assistance and extension by experts, rather than empowering farmers as innovators or as agents of diffusion. Yet participation was not, perhaps, as necessary here because this was largely a top-down diffusion of technology to produce for a market that Trustea created. While this was not strictly a case of "contract farming" it was similar, and suggests that participation and inclusion might be less important in cases where commercial actors are supplying both the technology and the market, rather than targeting food security and poverty among small farmers.

3.2. Support to Hypothesis 2: Leaders, intermediaries and champions are key to innovation pathways

Leadership is widely seen as essential to innovation pathways. Kohl and Linn (2021) specify three types of leadership as essential to scaling in particular. One type, what they refer to as *leaders*, are actors who are "committed to seeing scaling through to success, willing to make decisions, and able to mobilize others to support of scaling goals, strategy and tactics." A second type, what they call *intermediaries*, engage in "undertaking or facilitating activities like convening, systems analysis, boundary spanning, strategic planning and goal setting, advocacy and communication, process facilitation and people management, networking and coordinating, monitoring and evaluation, and financial and costing analysis."[12] Kohl and Linn, and especially other literature references *champions*,[13] people of influence in the relevant sphere because of their social status, position, power, control of or access to resources, connections and social network, or other forms of legitimacy that allow them to influence others. Many of the cases strongly illustrate the importance of leadership, particularly intermediaries.

Balde Cheio (Brazil) (Chiodi Bachion et al., 2022) had Embrapa as its lead agency, and one particular individual was cited as "the initiative's major unifying factor, because of his tremendous charisma, passion for the subject, proactivity, easy communication with farmers, great motivational skills, and solid theoretical and practical knowledge" (Chiodi Bachion et al., 2022). These comments imply that the relevant leadership skills were *technical*, to guide the innovation process; *personal*, to inspire innovators with an idea and potential impact; networking and advocacy, to mobilize and engage with partners; and *boundary spanning*, to effectively facilitate collaboration and cooperation between diverse actors and constituencies, and particularly to form

11 Cereal systems initiative for South Asia—Mechanization and irrigation.

12 Intermediaries are similar to the concept of brokers introduced by Klerkx and Gildemacher (2012) (see also Klerkx et al., 2009), but much more broadly defined. Klerkx and Gildemacher assign brokers three principal roles in innovation: bringing together actors, facilitating their interaction (including building coalitions or partnerships), and promoting the flow of information. As applied to the scaling phase, we find that intermediaries do play these roles *and also* undertake many other tasks that innovators might lack the skills, capacity, resources, motivation or incentives to do. This concept was first developed by Cooley and Kohl (2005), simultaneously with a similar concept, the resource team, developed by WHO ExpandNet (2010) in their scaling approach. As an example, Klerkx and Gildemacher (2012, Box 3.25) call iDE a broker in the same case we refer to here as the Mechanization Initiative in Bangladesh. We agree, but maintain that iDE went much further: it arranged partnerships with agricultural machinery companies, managed those relationships, promoted demand, refined the business and delivery model, advocated with the government for political and in-kind support and cooperation, developed the local service provider business case, identified local entrepreneurs to act as service providers, and arranged microfinance support. In roles like these intermediaries come closer to the role that venture capitalists play in helping investments go to scale, except they don't bring investment capital with them.

13 Champions are particularly present in the literature on scaling and impact pathways in global health, where the public sector plays a large role and advocacy for policy and budget are necessary. However, they also appear in agriculture and other more commercial sectors. They play a prominent role in the widely used ExpandNet/WHO scaling framework; see Simmons et al. (2021), who note, "one of the key principles from ExpandNet guidance is to seek to identify and nurture champions and to engage them early and continuously in ongoing dialogue" and the need to sustain support in the face of turnover by high level champions. See also Kohl and Linn (2021), for whom champions are closely linked to participation and inclusion; the greater the latter, the more champions can be identified with the motivation to advocate for the innovation.

and manage effective partnerships. However, it is not possible to determine how much of a role each played. What is clear is that Balde Cheio would not have been successful and replicated to other sectors in agriculture without "the strong leadership of Embrapa researchers ... from its inception to the present ... building a clear vision of the organization's potential and [addressing] the problems around technology transfer."

Andhra Pradesh Natural Farming (India) (Khandelwal et al., 2022) hinged on leadership both at the top of RySS (the organization driving the innovation and scaling), and at the community level. Looking more closely at the community level, this type of leadership comprised local farmers who championed the approach, served as examples to other farmers, and shared the technology and practices and helped adapt it as needed. A role for champions was particularly appropriate for a distributed innovation approach and farmer-to-farmer dissemination and scaling. Kohl and Linn (2021) explicitly acknowledge this role in calling to "complement leaders with champions at all levels and parts of the ecosystem to support advocacy."

Aqua Digital Irrigation Monitoring System (Brazil) (Chiodi Bachion et al., 2022) was developed by a business administrator, a graphic designer and an electrical and electronics engineer who came up with the innovation, created a company and mobilized funding. The CEO has been particularly important in media, marketing and fundraising, drawing on her skills as a speaker and communicator. This type of leadership seems to be particularly important in the cases of scaling that occurs through social enterprise growth. **Safe Harvest (India)** (Khandelwal et al., 2022) is another example of an innovation pathway through social enterprise growth. The company itself both led the effort and served as an intermediary. It organized farmer organizations and trained them to grow pesticide-free food for a supply chain; developed a credible certification system; and established downstream marketing and distribution linkages to consumers and stores. The original leaders of Safe Harvest came from a well-established NGO, bringing years of hands-on experience working with small and marginal farmers and farmer networks to build partnerships (referred to as collaborative capacities in the case study) for implementation and financing.

Other cases illustrate the roles that large external actors can play in absorbing costs and reducing risks for smaller actors and partners—key leadership and intermediary roles. The scaling of **Sahel Rice (Senegal)** (Kohl, 2016c) was led by a USAID project (Projet Croissance Economique) whose Chief of Party and project team partnered with organizations or groups to innovate and implement solutions to address bottlenecks; convened and facilitated multistakeholder partnerships; and engaged in risk mitigation to incentivize private actors to develop and implement their innovations. **Trustea (India)** (Khandelwal et al., 2022) leadership came primarily from Hindustan Unilever and a few other large tea processors and sellers. They also worked as intermediaries training and organizing farmer organizations to grow tea, developed a credible certification system and created demand. Much of this involved mobilizing partnerships with a variety of growers, NGOs involved in certification and the public sector. These large commercial actors were essential to organizing and managing those partnerships; while the big companies benefited, they were able to create synergies and a positive-sum game so that the gains were widely distributed.

The **Upper Tana–Nairobi Water Fund (Kenya)** (Mati et al., 2022) was built by partners convened under the leadership of The Nature Conservancy, a large international NGO. In addition to organizing, convening and facilitating a win-win partnership between stakeholders who normally would not collaborate, this NGO led and managed the initial proof-of-concept phase, leveraging its international expertise in water funds. Lastly, the **Mechanization Initiative (Bangladesh)** (Kohl, 2016b) combined leadership with the intermediary role in the USAID project team, a partnership between the research organization CIMMYT and the market facilitation NGO iDE. CIMMYT identified technologies and engaged in action research to modify, adapt and improve them. iDE worked primarily as an intermediary. Initially their role was to mobilize partnerships with large private agricultural machinery companies. Subsequently they supported those companies in creating demand and filling in gaps in the value chain, e.g., creating viable repair services and parts supply. One of the key lessons from the Mechanization Initiative that was representative of the intermediary role is the amount of "invisible" work and resources that was required to manage these partnerships on an ongoing basis. The project eventually had to hire one full-time staff member for each private company partner.

Kuroiler Chickens (Uganda) (Foy, 2017) again provides a counter-example. Arizona State University led the introduction of this Indian poultry breed in Uganda and worked closely with Uganda's National Animal Genetics Research Center. As both were primarily research organizations—the latter an example of a National Agricultural Resource System (NARS), neither had the mandate, motivation or resources to function as an intermediary or direct implementer for commercialization. They initially failed in their leadership role to engage other actors to fill these roles, e.g., commercial partners that could address gaps in the value chain and provide hands-on technical support to adopting farmers. It was not until those gaps threatened the entire scaling effort that a commercial partner was successfully brought in to fill these roles. This case illustrates a common problem for CGIAR centers and other agricultural research organizations: their local partners are usually NARS that have complementary research capacities but not the ability to support commercialization.

Drought Tolerant Maize for Africa (DTMA)/Hybrid Maize (Zambia) (Kohl, 2016a) also suffered when CIMMYT, which led the development of the varieties, provided little support for commercialization and scaling in Zambia and elsewhere. CIMMYT's role was largely limited to sharing its germplasm with private and public seed breeders and providing technical assistance for seed multiplication. Scaling/commercialization, especially market creation and demand, was left to diverse mostly private actors. It became very apparent that commercial seed companies had little incentive to invest heavily in promoting DTMA as these varieties were among many maize varieties in their portfolios and not necessarily the most profitable. This lack of leadership in the scaling phase was a clear detriment to scaling up; while hybrid maize in general did go to scale because it was in the interest of the commercial seed producers in Zambia and was supported by extensive public sector subsidies for both inputs and the purchase of output. By contrast, DTMA benefitted from neither, nor was the impact of climate change so regularly present at the time that farmers were looking for solutions to drought and its other manifestations; need doesn't equal demand. While all of these factors played a role in explaining the fact that, at the time the case study was written, DTMA represented a tiny fraction of the maize seed market, the lack of leadership by either the public or private sector were probably the most important.[14]

Lastly, **PICS Bags (Kenya)** (Foy and Wafula, 2016) is an unusual case. The bags were developed by a Purdue University research team, who also drove the initial introduction in Kenya (and several other countries) and established a foundation for scaling. This included identifying a manufacturer/wholesale distributor and supporting initial awareness building. Scaling was thereafter driven by a combination of a USAID project (Kenya Agricultural Value Chain Enterprises or KAVES) and local and international NGOs. Because of the bags' unique characteristics—affordability, huge return on investment, ease of proper use without extensive training, minimal change in existing agricultural practices, and relevance to important challenges facing farmers—spontaneous diffusion and adoption became the driving forces of scaling without a need for leadership. This illustrates a case where an innovation itself is so appealing, scaling occurs largely spontaneously. The example is problematic because innovation funders often expect this to be the typical case, whereas innovations with such characteristics are actually quite rare. Thus common practices, or the lack of them, to support innovation and scaling are premised on the assumption that most innovations are like PICS Bags, when in fact few are.

3.3. Support to Hypothesis 3: Innovation pathways should be iterative, adaptive and flexible

The notion that innovation and scaling should be iterative, adaptive and flexible has reached wide currency. In great part this is due to two reasons. First, approaches and culture from Silicon Valley around innovation and social entrepreneurship, and the technology sector generally, have increasingly influenced international development theory and practice over the past twenty years. This is especially because of the influence of large foundations whose fortunes come from the technology space play an ever more important role (e.g., the Gates Foundation was started in 2000, see Chang, 2018). Secondly, despite this, many international donors and research actors are aware that they continue to practice a rigid approach to innovation and scaling, often driven by legal, regulatory and bureaucratic contracting requirements. This has led many observers to blame their inflexible approach for the failure to advance very far along innovation pathways (e.g., Woltering et al., 2019).

To articulate a specific hypothesis regarding the importance of adaptability, we draw from Minh et al. (2021). They define five components of an adaptive scaling framework which they developed through "an iterative, action-research-for-development program on farmer-led irrigation," and we draw on two of these components to specify our hypothesis. According to these, innovation pathways should be:

- Reflective, i.e., reflects, manages and responds to dynamic and changing circumstances throughout the scaling processes.
- Adaptive, i.e., adjusts … the scope, capacity, and responses to and management of the strategy to the evolving dynamics of new system properties throughout the scaling processes.

It is important to note that in some cases adaptation and iteration was confined to either scaling or to innovation, in other cases both. The evidence below suggests that to some extent they are substitutes, as the more an innovation is adapted to the local context and needs, the fewer obstacles are encountered in scaling that need to be adapted to. However, on balance, it appears that adaptation is critical throughout the innovation pathway.

In **Balde Cheio (Brazil)**, Chiodi Bachion et al. (2022) the technical assistance delivered by the demonstration units and instructors was "adapted to the regional condition, producer needs for financing, property management, content and technical assistance" and to each property. The delivery structure was shaped progressively, as those interested in technologically developing the chain organized diverse arrangements for local implementation. In sum, it appears to have been adaptive in terms of the content of the innovation, an emergent process with the technology being introduced step by step according to farmer needs and reality. As is perhaps evident, an iterative and adaptive approach is complementary and synergistic with inclusion, allowing input from participants to be integrated dynamically as new experience and lessons emerge.

Likewise, the intervention packaged introduced by **ILPF (Brazil)** (Chiodi Bachion et al., 2022) was constantly evolving, adapted to "regional characteristics, weather conditions, the local market and farmers profiles." This was also true of the financing approach, which required significant changes to existing practices and instruments by the banks involved who were not accustomed to financing an integrated systems model. The innovation was adapted through an iterative "interaction between farmers' knowledge and 'formal' knowledge" (Chiodi Bachion et al., 2022). Modifications to the funding approach were particularly critical to addressing financial obstacles that had stalled scaling; these kinds of obstacles in financing and implementation are common, and often recur and arise repeatedly as sequentially greater levels of scale lead to encounters with different or new systems.

Adaptation is inherent to the approach to innovation found in the **Andhra Pradesh Natural Farming (India)** (Khandelwal et al., 2022) case; it was distributed, co-creative and demand-driven. Farmers themselves experimented with various natural farming approaches and principles, developing their own innovations

14 Cf. Chivasa et al. (2022): "Despite the importance and benefits of accelerated varietal turnover to climate change adaptation and food security, the rate of maize varietal replacement in SSA is slow.… Slow varietal turnover is affected by complex cross-sectoral and cross-disciplinary issues that require appropriate policy interventions" (emphasis added). This confirms the importance of systems change, institutional innovation and the provision of public goods which in turn require appropriate leadership and intermediaries.

and applications, and the farmer-to-farmer diffusion and scaling approach encouraged new adopters to do likewise. "Thus, Andhra Pradesh Natural Farming evolves as farmers find new crop combinations and apply natural inputs in different ways" (Khandelwal et al., 2022). At the same time, the case illustrates one of the tensions in using an adaptive approach: constant innovation and especially adaptation to local and individual circumstances and contexts makes it difficult to achieve economies of scale and scope and if anything, can actually increase the unit costs of adoption. While not necessarily true in this case, as with systems change and optimal scaling, it illustrates the need to balance application of this and the other principles tested with these cases with the implications for costs, time, effort and resources.

During the implementation of the **Sahel Rice (Senegal)** project (Kohl, 2016c), it quickly became apparent that the core focus needed to be on addressing weaknesses in the rice value chain; the "innovation," new rice varieties had been introduced and scaled in the 1990s but without realizing anywhere close to the full benefits of their genetic potential. Managers adopted what Kohl (2016c) characterized as a virtuous spiral model, identifying and addressing the most important immediate bottleneck. When this led to increased production or throughput in the value chain, it revealed the next bottleneck, which was addressed through new institutional and systems innovations or strengthening. This appears to be a form of the plan–do–study–act approach that has become foundational to trial and learning approaches in many sectors, especially health and education (cf. Coury et al., 2017). One consequence, however, of the logic of finding enough adopters to reach a critical mass, i.e., a commercially viable market and economies of scale, was that it required starting with larger, wealthier and more commercial farmers. Once this scale had been achieved it became worthwhile for commercial actors to address additional obstacles as they arose. This alignment of social objectives with commercial realities illustrates once again that innovation pathways require an adaptive and iterative approach, in this case resetting who the target customer needed to be.

The initial failures of **Kuroiler Chickens (Uganda)** (Foy, 2017) did lead to subsequent adaptation of the scaling strategy to address them, specifically engagement of a commercial partner to produce, market and deliver Kuroiler chicks. The case highlights the importance of having in place formal monitoring, evaluation, adaptation and learning (MEAL) processes that can quickly alert implementers to obstacles that emerge and need to be addressed. In that regard this is a useful negative example of what happens when adaptation, iteration and flexibility are delayed. A comparative example is the **Mechanization Initiative (Bangladesh)** (Kohl, 2016b) case. Some of the machines selected had problems in terms of usability, but CIMMYT and iDE monitored farmers' reactions and sales data and were quickly alerted to these issues. CIMMYT worked with farmers to adapt and modify the machines to suit farmers' needs and constraints. The business model was also adapted, changing from a direct sales to farmers approach to a service delivery model and from a focus on the target crops or rice and other cereals to the agricultural products where demand had unexpectedly manifested, e.g., fish farming, garlic and onions. Recognizing the importance of being adaptive and responsive to customer demand, the project enhanced its MEAL system and put into place a dynamic, near-real-time dashboard of who was buying what machines for what crops and purposes, and adjusted its marketing targets and activities accordingly and frequently.

3.4. Support to Hypothesis 4: Innovation should have characteristics that facilitate progress along innovation pathways and achieving large-scale SAI

Ever since the seminal work of Everett Rogers in the 1960s (see Rogers, 2003), there has been a recognition that innovations may possess characteristics that facilitate successful diffusion. A vast literature has since developed on these characteristics, and in the past 20 years a number of assessment tools have been developed for application to scaling agricultural innovations in particular (see Cooley et al., 2016; Jacobs et al., 2018; Kohl, 2018; Linn, 2022 for a comparison). The Agricultural Scalability Assessment Tool (ASAT) (Kohl, 2018), developed for USAID in the context of funding for innovations provided by the Feed the Future program, is currently being applied to identify those innovations with potential scaling and worthy of further investment. The ASAT has some 40 criteria, but we developed a simplified version of nine *criteria* that seemed, *ex ante*, to be most likely to facilitate progress along an innovation pathway:

1. The innovation addresses a felt (subjective) need, i.e., real potential demand and not objective need as identified by external technical experts, that is important to potential adopters (this is best identified by participation and inclusion, illustrating again the interdependency of these hypotheses).
2. The impact is tangible and easily observable to potential adopters.
3. The innovation is relatively simple with few components, i.e., easy for users to implement without extensive training or technical support. In cases of a combination or bundle of innovations, it generates significant benefits even if the entire bundle is not fully adopted or implemented correctly.
4. The innovation is affordable for potential adopters given their wealth and income constraints, without having to rely on external financing or otherwise put at risk the working capital they need to produce for the next season or year.
5. Adopters can expect benefits along multiple dimensions, either tangible (e.g., productivity, income, time-saving, health) and/or intangible (e.g., ease of use).
6. The innovation aligns with existing social norms, agricultural practices, tools and equipment, and thus requires little behavior change or additional complementary investment.
7. The benefits are relatively robust and reliable, i.e., are relatively consistent over time with low risk or variance.
8. Superior effectiveness is established relative to current solutions and emerging alternatives in similar contexts.
9. The innovation reduces risk or increases resilience, in addition to any increase in returns it may have.

Some of these may seem like common sense, yet they remain overlooked in many agricultural innovation efforts which tend to maximize the impact on productivity or other objectives like climate resilience rather than how easily it can be adopted and used by, and aligns with the *priorities of potential adopters*.

The **Water Harvesting (Kenya)** innovation (Mati et al., 2022) clearly met a strongly felt need among small-scale farmers practicing rainfed agriculture, had clear benefits that were better than existing alternatives, had multiple benefits (useful for crops and personal consumption), had tangible benefits in terms of reducing time for getting and carrying water, was simple to use, reduced risk and increased resilience. The ability of this innovation to reach some scale without needing strong leadership or adaptation speaks to the strength of the original design in terms of these particular characteristics. **Solar Powered Irrigation (Kenya)** (Mati et al., 2022) also did well on these criteria; it met a need and was tangible, reliable, superior to existing solutions and supportive of resilience. Perhaps the characteristics that stood out most were its relative simplicity and robustness. Providers developed complete kits that included drip irrigation and piping, as well as offering assembly and ongoing technical support, or both, to facilitate adoption.

PICS Bags (Kenya) (Foy and Wafula, 2016) aligned with almost all of the criteria. Post-harvest losses were a huge problem for farmers throughout the year, and the bags were inexpensive and highly affordable, extremely simple and easy to use with only one component. The only behavior changes were to dry the crop to low moisture content and to store it away from rodents, and the results were easily visible after a few months. The bags lasted for a few years without a loss of effectiveness or impact. By allowing farmers to store their harvest with few losses and sell when prices are higher, they significantly increased food security and resilience and improved income.

The **Mechanization Initiative (Bangladesh)** (Kohl, 2016b) formed a natural experiment, as it introduced four machines whose characteristics differed across many of the innovation criteria. Perhaps the most impactful at large scale, at least initially, were axial flow pumps, which met a clear need by rice and fish farmers for pumping water and were relatively inexpensive. They required almost no change in behavior or agricultural practices; in fact one of their attractions was that they were easier to use, especially in cold weather, and could be powered by the diesel engines already in use. By contrast, self-powered reapers were much less successful due to being more expensive, replacing the labor of workers who had been traditionally hired to do both reaping and threshing (who pushed back by refusing to do only threshing), and being difficult to use especially in muddy conditions. The clearest (negative) example were bed planters, which were so heavy and cumbersome as to make them challenging to manipulate and operate in a muddy field, especially given the height and weight of many Bangladeshi farmers. The innovations that were easier to use, affordable, simple, addressed existing felt needs, produced superior outcomes and required minimal changes in agricultural practices were more likely to be adopted than those that did not have those characteristics.

Another counter-example lies in **Drought Tolerant Maize for Africa/Hybrid Maize (Zambia)** (Kohl, 2016a) and its difficulties. In particular, it did not address a felt need, and the impact was only observable in drought conditions. The package was complex and required behavior changes, and the benefits were two-dimensional: improved harvest under poor rain conditions, and greater resilience. Even those farmers who did adopt it usually only did so after a few years of poor harvests from drought when objective need became actual demand, and even then only as part of a portfolio approach of planting different seed varieties to diversify risk.

Balde Cheio (Brazil) (Chiodi Bachion et al., 2022) addressed a felt need, had a tangible and visible impact, produced benefits across multiple dimensions, was better than current practices, reduced risk and improved resilience. The downside was that was complex with multiple components, requiring significant changes from current practices. Significant adaptation to local circumstances was required, making scaling more challenging. These latter characteristics are all consistent with the fact that implementation required significant and ongoing training, technical assistance and extension support. If this had not been supported by the public sector and substantial funding over an extended period, scaling would have proven impossible. **Aqua Digital Irrigation Monitoring System (Brazil)** (Chiodi Bachion et al., 2022) addressed a need for timely information and guidance and fit with other criteria; however, it did require significant changes in behavior, was complex and required technical support to ensure accurate application of the entire package. This, along with its high cost, is why it was best suited for more sophisticated medium and large farmers.

Because **Safe Harvest (India)** and **Trustea (India)** (Khandelwal et al., 2022) spanned the value chain from producers to consumers, they confirmed the importance of aligning innovations with the needs and demands of both. These two cases offered innovations with multiple benefits for better management, health and market access, and also improved resilience. On the other hand, their complex new practices required significant change in behavior, and their relative success was dependent on the high levels of profitability involved and ability to finance significant technical support and extension services.

Kuroiler Chickens (Uganda) (Foy, 2017) met several of the criteria, such as significant and highly visible benefits in the chickens' increased and rapid meat and egg production compared to indigenous breeds. However, they also had important negatives that impeded successful scaling, most importantly that they required significant changes in animal husbandry practices, e.g., investing in fencing and supplemental feed and vaccinations of chicks that was unnecessary with domestic breeds. Moreover, impact was not robust or stable without strict adherence to these practices. Because they are hybrids they were much less affordable, as new chicks had to be purchased from a breeder. This is an important illustration that these characteristics are not simply a list of which some can be met and others not; in many case just one or two criteria can seriously affect scaling results despite the other characteristics. For any individual innovation, not all characteristics have equal importance or weight.

3.5. Support to Hypothesis 5: Innovations must be packaged with viable funding and implementation models and bundled with systems change

The innovation and scaling literature uses terms like packaging and bundling to refer to elements of an innovation beyond a single core technology or institutional characteristic. While the meanings of packaging and bundling often overlap—so much so that we have deemed it necessary to consider them as parts of the same hypothesis—they refer to two concepts that are important to differentiate.

Packaging refers to the fact that innovations, or combination of innovations, to be scaled or implemented, have to be combined with a viable delivery method and payment/business/funding model to form an innovation package. The delivery method and funding or business model can themselves be innovations, and can often be more important and/or innovative than the innovation itself. Note that this definition differs from what is often called a technical package (which might describe, for example, how Balde Cheio at the technical level packaged feed, animal housing and health).

Bundling refers to the fact that moving a specific innovation or innovation package further along the innovation pathway often requires it to be supported by systems changes and/or institutional innovations (similar to the concept of vertical scaling).[15] These systems changes can range from strengthening or filling in gaps in value chains or market systems, e.g., Sahel Rice, to changes in the public policy and institutional enabling environment, e.g., Trustea, to affecting change in social or cultural norms or mindsets, e.g., Andhra Pradesh Natural Farming (see Woltering et al., 2019; Minh et al., 2021).

The **Mechanization Initiative (Bangladesh)** (Kohl, 2016b) initially assumed that its agro-machinery partners would provide financing, marketing and distribution, but this was not the case until the private partners were sure that there was a large, viable market. When sales to individual farmers proved disappointing because of affordability issues, the business model was shifted to a local service provider model. Even with the new business model affordability remained an issue, however, so that the initiative had to partner with micro-finance institutions to provide financing. Similarly, the project had to bundle the machinery with value chain strengthening, such as arranging for repair services and a reliable supply of (imported) spare parts. This is a good example of how a donor-funded project can absorb the initial costs and function as a leader and intermediary to put in place an innovation package bundled with systems changes and institutional innovations until the private sector is convinced that it is profitable for them to take it forward.

Another is **Sahel Rice (Senegal)**, Kohl (2016c) which followed up on the 1990s introduction of improved varieties of rice in the Senegal River Valley, where most farmers never came close to realizing the new varieties' productive potential. Sahel Rice's long list of systems changes included a certified seed system, rehabilitating rice milling, reviving links with urban market, encouraging entrepreneurs to provide machinery services, and restoring and repairing irrigation infrastructure. The success of all was preconditioned on a highly supportive policy enabling environment (systems change), which the government put in place following the world food crisis of 2008/09. Supportive policies included a variety of price supports, subsidies and regulatory controls along with an implicit guarantee that reduced risk for investors and donors. The systems changes have endured and rice productivity has begun to realize its genetic potential, but the "commercial" system remains heavily reliant on government support and intervention. Still, it compares favorably to **Drought Tolerant Maize for Africa/Hybrid Maize (Zambia)**, Kohl (2016a) another "commercial" business and delivery model. While the seed varieties were produced, marketed and distributed by mostly commercial seed companies, their progress to scale was predicated on a major institutional innovation—a donor-funded national seed certification system. This systems was foundational not only for the widespread adoption of hybrid maize but for the country becoming a major exporter of maize seed for Southern and Eastern Africa. Other countries and markets found they could depend on the quality and reliability of these imported seeds. In Zambia, scaling was heavily dependent on massive public sector subsidies for the purchase of seeds and fertilizer and a guaranteed market for hybrid (not specifically drought tolerant) maize. These subsidies were similar to those present in Sahel Rice, but not in size or impact. In Zambia, the subsidies were so large as to fuel excessive production and created severe distortions that virtually eliminated commercial buyers. As a result, they eventually become fiscally unsustainable. These two cases make the case for the importance of institutional and systems change and especially public policy, even within commercial innovation pathways, but also illustrates the careful balance that between adequate support, perverse incentives and fiscal sustainability that needs to be achieved when governments provide support to private markets.

P1+2 (Brazil) (Chiodi Bachion et al., 2022) was able to reach over 200,000 families between 2007 and 2020 under two successive Workers' Party governments. The implementation model was done by contracting under the Brazilian Tenders Law (8.666/1990) and the federal government's agreement model. When these two structures became an obstacle to implementation, the government effected changes in the legal framework that were critical for the functioning and expansion of the program.[16] These changes allowed scaling to continue and even accelerate, a perfect example of combining iteration and adaptation with bundling. However, when political parties and leadership shifted in 2016, funding

15 This is in the context of horizontal, vertical and functional scaling up (also referred to as scaling out, scaling up or scaling deep). This is used by many authors; Hartmann and Linn (2007) define vertical scaling up as "creating the organizational and political framework needed to permit going to a larger scale," and horizontal scaling up as "the expansion of coverage of a project, program, or policy across more people and greater space."

16 Specifically, the changes in the legal framework "made it possible to formalize contracts by means of bidding waivers with private non-profit entities previously accredited by the [Ministry for Social Development] and conferred agility in accountability by shifting the focus from services to the final product (delivered technology)" (Chiodi Bachion et al., 2022, p. 26).

evaporated. Thus the reliance on federal funding as the business model, i.e., packaging, appears to have been both a blessing and a curse in terms of long-term financial sustainability.

While packaging and bundling are often necessary for successive scaling, the particular choices that are made can often either limit the scale and impact achieved, or confine it to certain, usually more well-off, demographic. This is particularly true when the business model or funding mechanism is significantly commercially driven, i.e., the innovation user or adopter pays, even when that may be partly subsidized. Two of the Brazil cases illustrate this point. In the case of **ILPF (Brazil)** (Chiodi Bachion et al., 2022), public and private partners cover the costs of developing and improving the technology package and of technical referral units, but most of the cost is borne as individual investment by (mostly large- and medium-scale) farmers. The model also included the creation of specific credit and financing lines in the context of a sectoral plan for agriculture—systems changes in policy and financing mechanisms. This business model was actually a blend of packaging and bundling, and has proven more sustainable than P1+2's politically dependent funding, at least for those adopters who can afford it.[17] Likewise, the scaling of **Aqua Digital Irrigation Monitoring System (Brazil)** (Chiodi Bachion et al., 2022) was packaged with a funding model that relied mostly on private financing sources and customer fees, making it impervious to political vicissitudes, but like ILPF, limiting scale. As a wholly private social enterprise, furthermore, it was not bundled with any systems changes. While successful commercial pathways cases do occur where there is little or no involvement of the public sector, there are so many counter-examples that the presumption should remain that public sector support is usually necessary, especially at larger scales such as the national,[18] as it is in many developed countries where supportive agricultural policies and subsidies are ubiquitous.[19]

Many other examples illustrate the trade-offs found in scaling numbers, reach and demographics depending on the packaging or bundling chosen. **Water Harvesting (Kenya)** (Mati et al., 2022) was characterized by an *ad-hoc* mix of partial donor, NGO, public and end-user financing, and estimate that by 2021, 10,000 farm ponds had been excavated in the three counties studied, reaching at least 100,000 people. While this was an important achievement for those people, the rural population of the three counties was ∼2.1 million, suggesting that scale was a fraction of potential demand. Meanwhile, **Solar Powered Irrigation (Kenya)** (Mati et al., 2022) illustrated what happens when the challenge of a viable business and delivery model is only partially addressed. It did have a viable private sector delivery model and there was a small and growing market in the one county studied, and probably elsewhere in the country. However, Mati et al. (2022) conclude that sustainable impact would have been much greater if some actor had invested in increasing market awareness, achieving lower prices through economies of scale and subsidizing or otherwise lowering financing costs. The packaging was good but the bundling with public goods was inadequate.

Some successful cases were themselves examples of systems change *as* the innovation. **Safe Harvest (India)** (Khandelwal et al., 2022) was one, providing pesticide-free agricultural products to urban markets through value chain linkages. **Trustea (India)** (Khandelwal et al., 2022) achieved something similar through its tea certification standard and traceable chain of custody. The **Upper Tana–Nairobi Water Fund (Kenya)** (Mati et al., 2022) was a system-changing institutional innovation, and included a viable funding model through a donor-financed trust fund, as well as an implementation model through its secretariat, electricity, water and sanitation companies and local NGOs. The completeness of this package seems to explain much of its success and sustainability.

Lastly, **PICS Bags (Kenya)** (Foy and Wafula, 2016) were again the outlier among technological innovations. They went to large scale, sustainably, based solely on an end-user-pays model with no elements of packaging or bundling. The project identified a domestic plastics manufacturer for production and then leveraged existing delivery mechanisms, both traditional agro-dealers and independent distributors on bicycles and motorcycles. Central to this was the very low unit cost and high returns for end users, such that it was affordable for them while allowing producers and distributors to make a good return.

3.6. Support to Hypothesis 6: Partnerships are critical for innovation, scaling and systems change

Partnerships are both critical on their own and often combined with bundling of systems change and participation and inclusion in recommendations regarding good practice in moving forward along innovation pathways. This is in large part because participation and partnership are interdependent and mutually reinforcing. In terms of achieving impact at large scale, partnerships are seen as critical because often no one actor has the necessary resources, be they financial, operational or political, to succeed on their own. This is particularly true when innovators are researchers and lack those resources (or the mandate or ability to act as intermediaries), or when the innovation itself is institutional or a form of systems change, bundled with such changes, or packaged with financing models. In commercial innovation pathways, as demonstrated in the previous section, partnerships or at least some involvement of the public sector is required to ensure a supportive policy enabling environment, if not to provide specific types of public support.

Partnerships for innovation vs. for scaling tend to have their own separate literatures. For that reason, we cover partnerships in innovation under participation and inclusion, and focus on partnerships in scaling or systems change in this section. Partnerships were, indeed, found in most of the case studies and

17 Chiodi Bachion et al. (2022) conclude that the scale achieved is still low compared to its potential precisely because it was packaged with a quite restrictive financing model.

18 See in Lesson #9 in Kohl and Linn (2021), which states: "Public and private actors—consider and address the appropriate role for the government/public sector in a predominantly private scaling pathway, and the role of the private sector in public scaling pathways."

19 Cf. OECD (2022), which shows that public support "in 2019–21, representing 17% of gross farm receipts in OECD countries" had experienced a 2.4× increase since 2000.

we can say with some confidence that partnerships in most cases facilitate success. The more interesting questions revolve around what constitutes a *good* partnership and how to create or sustain one. Drawing on several sources (notably Barrett et al., 2020), the literature suggests certain characteristics of good partnerships:

- A shared commitment to a common vision and alignment of that collective vision with individual incentives and interests.
- Mechanisms to ensure effective coordination of individual actions.
- Clear definition of individual roles and sharing of responsibilities and risks.
- Effective accountability mechanisms based on monitoring of mutually agreed key performance measures and enforcement of agreed actions.
- Sufficient financial and other resources, management and governance structures to operate effectively and sustainably.

The **Upper Tana–Nairobi Water Fund (Kenya)** is a strong example of partnerships in multiple dimensions, in this case across a water supply chain. The partnership between upstream farmers in the catchment area and downstream users was initially organized and facilitated by The Nature Conservancy, and then was transformed into a fully incorporated trust including public, private and development actors and communities. This succeeded despite the interests of upstream and downstream users not being clearly pre-aligned, illustrating the need for leadership to align disparate incentives. It was run by a Board of Management under a Board of Trustees, the latter representing diverse stakeholders that ranged from water, sewage and electricity parastatals to NGOs and community organizations. Management included a thorough monitoring system for financial and environmental outcomes. As such the innovation was both a financing and governance mechanism; the funding was initially endowed by donor partners and downstream users and replenished in payment for improved water quality.

Despite the fact that **Balde Cheio (Brazil)** (Chiodi Bachion et al., 2022) was driven by the government, partnerships were essential, especially between different levels of public actors within Brazil's decentralized federal government. These included technical assistance and rural extension agencies, linked to State and Municipal Agriculture Secretariats, and teaching and research institutions; private partnerships brought in cooperatives, dairy product companies, associations and agricultural federations. A strong governance mechanism was also important after Embrapa decided to transform the informal partnerships into a formal relationship and strengthen administration—a good illustration of the benefits of organizational over individual leadership in a partnership context. Partnerships were core to this innovation, and scaling would not have occurred at all or been very limited without them. These improvements in governance allowed for additional scaling to 50% more states and a 25% increase in both the number of technicians trained and in local partnerships.

P1+2 (Brazil) (Chiodi Bachion et al., 2022) benefited from an existing alignment of interests between the Workers' Party government and grassroots entities. It was *de facto* a public–private partnership between the Ministry of Social Development and a grassroots coalition ASA, "the result of a long process of institutional maturation … and the recognition of the importance of civil society's participation in implementing public policies" (Chiodi Bachion et al., 2022). On the other hand, **ILPF (Brazil)** (Chiodi Bachion et al., 2022) primarily partnered with commercial actors like Syngenta and John Deere. Here the Worker's Party government role was less about aligning interests, and more about public-private funding mechanisms and providing the leadership (by Embrapa) to manage the partnerships. Technologies were packaged with various forms of training and extension support supplied by partners.

Andhra Pradesh Natural Farming (India) (Khandelwal et al., 2022) was a partnership between a non-profit corporation spun off by the state government as a farmers' association, and the state government itself. It was implemented in partnership with local governments and women's self-help groups, the latter also being a source of financing for farmers. The state government provided funds for the association to manage these partnerships effectively. Local partnerships were co-creative and scaling largely horizontal and farmer-to-farmer.[20] The creation of this partnership, too, required an alignment between the values of natural farming and the politics of the state government at that time.

The other Indian cases are also partnership-driven. **Trustea (India)** (Khandelwal et al., 2022) began as a partnership between corporate tea processors and the Sustainable Trade Initiative, a Dutch organization comprising private companies, NGOs, trade unions and the Dutch Government. This then expanded to work with NGOs with standards and verification expertise, and eventually took the form of a multistakeholder governing council that also included the government regulatory agency. Despite the lack of pre-aligned interests between corporate processors and NGOs, the case validates the importance of a shared vision, clear mechanisms and governance structures in bringing such diverse and potentially oppositional interests together. It also supports the importance for successful partnerships of monitoring of key performance measures (standards compliance), integration with government systems, clearly defined complementary roles, and formalized relationships.

In all of the USAID cases, the USAID projects or USAID-funded innovators themselves played the partnership managing role. This worked better in some cases than others. **Sahel Rice (Senegal)** (Kohl, 2016c) featured partnerships with rice breeding research institutions, farmers' organizations, government agencies, and perhaps most importantly, informal coordination with other donors. The USAID project's lead role allowed for collective action and coordination of donor efforts and a multiplier effect on financial resources. The value-chain strengthening efforts by multiple donors were able to reach a much larger number of farmers than any one organization could have done on its own. Farmers' organizations, rice millers and other value chain actors

20 This however needs to be seen in light of the large organizations and significant money involved in rapidly scaling the "co-creation" and priming it as an investment opportunity, which has raised some potential contradictions with its horizontal partnership approach, not to mention its "zero-input" basis (Saldanha, 2019).

were key partners, as well as government parastatal banks and insurance companies.

The **Kuroiler Chickens (Uganda)** (Foy, 2017) case provides an example where the partnership approach was not initially successful because the initial partner didn't have the right complementary skills, in this case intermediary skills. Arizona State University's initial partner was a government research agency and enthusiastic supporter, but they were not capable of creating a supply chain of chick breeders and incubators and provide sufficient extension. This omission was eventually addressed by engaging a private partner, i.e. a partner with the right skills, the initial and prolonged delay caused a shortage of chicks for several years and nor the needed extension support. The national agricultural research system, in Zambia, was also the partner in developing **Drought Tolerant Maize for Africa/Hybrid Maize (Zambia)** (Kohl, 2016a), and this too fell short for similar reasons. Once the genetic material was made available, CIMMYT did not engage in partnerships to promote adoption, market development or demonstration, and drought tolerant maize reached very limited scale compared with hybrid maize generally.

4. Discussion

Here we make recommendations to the numerous actors working toward sustainable impact in SAI.

4.1. Innovation pathways must be participatory and inclusive

This was perhaps the hypothesis where the evidence was most ambiguous. On the positive side, there is clear evidence that consulting with and/or involving farmers in developing, testing, refining and scaling of innovations produces better results in two senses. They are more likely to be sustainably adopted and have greater impact because they are aligned with farmers' actual felt needs, existing practices, and constraints, e.g., financing and affordability, and they are more likely to scale because participation creates ownership and buy-in (the characteristics of hypothesis 4). Participation is important not just for farmers but other parts of the market system; it ensures production, marketing and delivery are profitable and therefore there will be a reliable, accessible supply, including to the last mile.

On the negative side, the extent of involvement must be weighed against significant costs of organizing, convening and aligning interests and vision. Scaling is almost always a multi-stakeholder process, but requires balancing the benefits of breadth and depth of participation necessary for success, as well as equity considerations, with the costs. Also, in the few cases where both the development and supply of technology packages and access to markets were provided by private actors for commercial markets rather than own consumption or local markets, participation was less important. Greater comparative or controlled research is needed on how the extent of participation affects outcomes in terms of improvements in productivity and incomes.

4.2. Leaders, intermediaries and champions are key to innovation pathways

In most of the cases, leadership played an important role at some stage. While more research is needed on the roles of leaders and other actors in innovation pathways, one of our major findings is that the need for leadership must be extended beyond the innovation phase to include intermediaries: organizations who facilitate scaling and/or systems change. Cases where one actor can lead the whole innovation process to the end of the pathway—large scale—are notably rare. It is unusual that all of the resources and capacities, and often motivation, of both leading innovation and facilitating scaling (intermediation) are to be found in one actor, especially when the innovator is a research organization. Leadership needs to be disaggregated by the stages or phases of innovation pathways, and specify the different skills and resources needed depending on the phase, type of innovation package, extent of bundling with systems changes, and current level of scale.

Investors in SAI innovation pathways can take one of three approaches to the leadership question:

- Identify and support existing innovation leaders with the capacity and skills to take end-to-end innovation pathways to scale and/or affect the necessary systems changes.
- Ensure that innovators who lack intermediary skills are partnered with appropriate public or private actors from the beginning who can take innovations to scale, e.g., commercial partners.
- Support intermediaries that function in between innovators and large-scale Doers and Payers.[21]

While partnerships, hand-off and exit strategies between researchers/innovators and intermediaries or large-scale partners make sense in principle, the very creation, organization and implementation of these strategies itself requires leadership or intermediary skills—and the commitment of all the organizational resources implied. Some of these functions that pertain to intermediaries are also difficult to achieve, given limited actual experience. Ethiopia's Agricultural Transformation Agency, a parastatal, is a well-regarded and widely-used example (see FAO, 2020) precisely because it is rare.[22] Although donor projects can function as intermediaries, they are rarely designed for the purpose. Accelerators, with whom there is substantial experience, can play this role to a limited extent, as the support they provide generally covers only the earliest stages of scaling or systems change. Much more applied research and many more case studies on these critical points are needed.

21 Payers are those actors who provide sustainable funding for an innovation or systems change at scale; Doers are the actors who have the capacity and skills to sustainably implement or operationalize an innovation or systems change at scale.

22 Chivasa et al. (2022) detail the successful updating of maize varieties in Ethiopia without describing the institutions that made it possible.

4.3. Innovation pathways should be iterative, adaptive and flexible

Many development efforts take the form of projects with rigid sets of activities, workplans and targets. By contrast, an adaptive approach starts with the premise that innovation pathways are ultimately involved in transformation of agri-food systems, and therefore are inherently complex and dynamic. To be effective, that systems transformation or innovation pathway process needs to adapt to this emergent process by constantly reexamining its assumptions based on actual experience and monitoring, and revising its vision, strategy, activities and tactics accordingly (see Woltering et al., 2019; Kohl and Linn, 2021; Minh et al., 2021). This is particularly true because necessary systems changes only become apparent as scale increases.

The evidence for an adaptive, iterative approach to developing innovations was almost universal, and these adaptive approaches need to apply even more so to scaling and systems change as context and relevant systems change at different levels of scale and scope.

Innovation pathways should therefore include multiple and continuous feedback loops and evidence generation to support these activities, building on monitoring and evaluation (M&E) with adaptation and learning (MEAL). Evidence generation does not stop with proof of concept at a pilot stage, and in fact even that needs to be revisited, as noted above, when scale increases and contexts multiply. Funders need to balance accountability for the overall goals and mission with flexibility in terms of specific crops, activities, pathways and strategies.

4.4. Innovation should strive to have characteristics that facilitate progress along innovation pathways and achieving large-scale SAI

A large literature suggests that innovations with specific characteristics have greater potential for achieving SAI (e.g., Cooley and Kohl, 2005; Jacobs et al., 2018; Kohl, 2018). Our cases also reinforced that technical innovations of products and services should be designed and developed to align with characteristics that facilitate scalability, including:

- **Relevance** to an important and subjectively felt need (demand).
- **Tangible** and easily observable impact.
- **Relative simplicity** with few components, so that the benefits are realized even when adoption is imperfect or incomplete (in terms of components of an innovation bundle), i.e. robustness.
- **Affordability** given wealth and income constraints, and adopter's aversion to putting their working capital at risk.
- **Benefits offered** along multiple tangible and intangible dimensions.
- **Alignment** with constraints to adoption and existing norms, practices, tools and equipment, minimizing the behavior change or additional investment(s) required.
- **Superior effectiveness** relative to current and emerging alternatives.
- **Reduced risk** and increased resilience, not just or only increased returns.

Nevertheless, we found that for innovations that didn't have these, bundling with systems changes, capacity building or strengthening Doers and Payers, or developing alternative business or delivery models that when innovation lacked these criteria did allow for scaling and advancement along innovation pathways—at a generally higher cost. Innovators, funders and implementers should make explicit choices about whether the benefits justify devoting the additional time, effort and resources required.

4.5. Innovations must be packaged with viable funding and implementation models and often bundled with systems change

Packaging comes out clearly in the case studies, and bundling a bit less so. Many innovations fail to scale not because the innovation combination doesn't produce value for end users, but because it isn't packaged with a viable business, funding or delivery model. One of our findings is that the meaning of packaging tends to differ between commercial and public sector innovation pathways. For innovations scaling through commercial pathways, it implies that all actors in the value chain are able to make money from the innovation. In public sector pathways, a multitude of political economy considerations are relevant beyond alignment with stated policy objectives, as many innovators and their funders have discovered to their chagrin.

The evidence was also supportive, though less strong, for the importance of bundling with systems analysis and change; sustainable scale can sometimes be achieved without it, but bundling increases the likelihood of success and can often take it much further than would otherwise be the case. Several CoSAI cases were in fact institutional changes bundled with technology packages and technical assistance, while the most successful USAID cases involved major efforts at strengthening value chains or were combined with extensive support and changes in the public sector enabling environment. The importance of bundling seems to depend heavily on the type of innovation, choice of scaling pathway (public, private, NGO, or some mixed approach), and alignment with the relevant systems implied by that scaling pathway.

Developers of an innovation need to identify from the beginning whether the innovation is already aligned with existing systems constraints or whether it needs to be bundled with systems change. If the latter, what time and resources are required, and who could lead that effort effectively? For systems changes and institutional innovations, do these require additional adjustments such as changes in social norms? Mapping and analysis of systems and the ambition of systems change—while important in a world of complexity and multiple, interrelated goals—need to be a careful balancing act with a practical assessment of the feasibility of organizational change and a realistic assessment of incentives and political will as well as costs and benefits.

4.6. Partnerships are critical for innovation, scaling and systems change

The evidence confirming the critical role of partnerships was very strong, though it also underlined how much work these involve to organize, operate and sustain. Successful partnerships reinforce and interact with some of the other recommendations, particularly the role of a lead actor or organizations in being willing to absorb the costs and compromise on some of its own interests for the greater good and to create public goods, even by private actors. They are also essential as the diverse political, financial and implementation resources needed at scale that are rarely found in one actor. Even when a single Payer or Doer is feasible, partnerships have significant advantages for sustainable impact at large scale by creating shared buy-in and ownership.

An overlooked part of partnerships that needs support, again interacting with other findings, is the issue of intertemporal roles, sequencing and complementarity. Funders, donors and the public sector are well placed to absorb initial risks and engage in risk mitigation. This can then allow the private sector to invest and assume the role of Doers and Payers.

Yet partnerships also take substantial time, effort and resources to create, manage and sustain, and require aligning a shared vision and creating trust. This is nowhere more true than in the public–private examples—where the work is also highly political. Different kinds of government administrations partner more successfully with NGOs to reduce poverty, or with commercial interests to boost growth and resource use. Vision and trust fundamentally define all of these partnerships and are no small considerations.

4.7. Conclusion

The case studies reviewed in this paper all achieved sustainable impact, though at widely varying degrees of scale. Some achieved relatively large scale, while others achieved more limited scale; all were successful in advancing adoption and implementation to some degree. The uneven success and limited scale achieved doesn't allow us to conclude that following these hypotheses ensures sustainable impact at large scale. The cases reviewed, and particularly the variance in outcomes among them, does allow us to conclude that NOT following these principles is likely to at best impede progress toward this goal, if not severely limit success.

Of the various hypotheses considered in this paper, perhaps the most significant failing traditional approaches to advancing along SAI innovation pathways is that many actors focus on *innovations* rather than *innovation pathways*. As such, they don't incorporate scaling as an integral component that needs to be taken into account at every step of the process. For example, by minimizing participation, they neglect demand in favor of need as determined by technical experts. By ignoring constraints at scale, they design innovations that are incompatible with those constraints—and either fail to identify viable implementation and funding models, Doers and Payers, or to anticipate the partnerships, systems change and institutional innovations needed, and the resources and leadership necessary to create these. They assume that proof of concept is sufficient and some never-clearly-specified Doers and Payers will magically materialize; perhaps the national government will do it, even in the absence of resources, implementation capacity and political incentives.

Furthermore, donor projects use a definition of scale which is often too limited i.e. simply getting to a large number of adopters in a fixed period of time. They ignore issues like the sustainability of incentives, production, delivery and implementation, and financing and other resources. By doing so, they overlook the need for investing in packaging and bundling with institutional innovations and systems and systems change. Even when they do so, they do this after progress along the innovation pathway is relatively well advanced, requiring retrofitting which can be expensive and time-consuming, rather than integrating these considerations into the innovation process itself.

Pursuing a broader approach to innovation pathways, and therefore leadership, increases the chance of achieving sustainable impact at large scale and the much-discussed but rarely achieved game-changing disruptive change. To do this requires a number of changes in approach, such as more participation, adaptiveness and flexibility, and usually partnerships. It also requires wholly different skills, capacity and resources, including a broader definition and role of leadership to include the intermediary role in particular than is found in traditional innovation and scaling approaches.

Importantly, then, the six hypotheses we have investigated here are very closely intertwined. Their synergies and interactions mean that none can be easily discarded. It is essential to consider them together as aspects of the same difficult pathways to a sustainable future.

Serious systems change, bundling and packaging, participation and partnership, iteration and adaptation: these all take additional time, money and effort. They mean recognizing a far higher level of complexity; the dynamic, emergent and unpredictable nature of the process; and, because they involve people and their organizations and enrolling their engagement and support, the inherently political nature of innovation pathways and especially their scaling components. Admittedly, this brings the rarely acknowledged political aspects back into innovation—a field that is attractive to so many precisely because it appears technocratic and politically frictionless.

Therefore, taking scaling seriously requires both a willingness to commit greater resources (or focus on a smaller number of big bets) and an increased appetite for risk. Rather than playing to the expectation that most projects will succeed in meeting their time-limited, numerically-specific targets (as when the World Bank and International Fund for Agricultural Development report that 70%−80% of their agricultural projects are at least moderately successful), innovation pathways that seek to have *sustainable* impact at *large* scale (commensurate with the size of the problem) will often fail to meet that much more ambitious target.

Yet if we are to achieve the Sustainable Development Goals by 2030, we must embrace that risk by adopting a portfolio approach often found in venture philanthropy. In this approach an expectation of a relatively large number of failures is offset by a few transformative successes which then change the lives of hundreds of millions, if not billions.[23] Current approaches are doing something very different: ensuring, with a high probability of success, time-limited impact in numbers that are overshadowed by the scale of need. In contrast, private venture capital has changed the world based on an acceptance—even a rule of thumb—that three out of four start-ups will fail (Gage, 2012). While the evidence and recommendations presented here are only a start and more evidence, examples and detailed guidance are needed, there are many lessons we have already learned well. Development actors who apply these to SAI innovation pathways will be more likely to successfully change the world's agri-food systems and achieve global goals for rural livelihoods, food security, resilience and climate change.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://wle.cgiar.org/cosai/pathways-for-innovation.

Author contributions

RK received extensive help from Paul Farah Cox of Scriptoria in the drafting and editing of this manuscript.

23 According to one representative source SoPact, characteristics of venture philanthropy include "targeting systemic change through collaboration (e.g. partnerships); a focus on scaled or scaling interventions at a sector level (systems change), use of a multi-stakeholder focus (participation and inclusion), long-term engagement ... in alignment with a systems change mindset, and agile M&E [for] swift adaptation of interventions as needed based on outcomes." To give but one example, the Draper Richard Kaplans Foundation (2022) claimed that out of their 168 investments totaling $70 million, 18 were having a significant impact on millions of people.

Funding

The research communicated as part of this paper was funded by the International Water Management Institute (IWMI) on behalf of the International Commission on Sustainable Agriculture Intensification (CoSAI).

Acknowledgments

Based on a research project conducted on behalf of CoSAI (Kohl, 2022). Extensive help was given by Paul Farah Cox of Scriptoria in the drafting and editing of this manuscript. The author wishes to thank Josefina Achaval Torre and Jonathan Wirths of the CoSAI Secretariat for the important research assistance they provided. This study relied significantly on three country case studies of innovation pathways and the author wishes to acknowledge the contributions of Lucian Chiodi and the Agroicone team, authors of the Brazil study; Apoorve Khandelwal and the CEEW team, authors of the India study; and Bancy M. Mati and the Resource Plan Ltd. team, authors of the Kenya study. Finally, this article would not have been possible without the ongoing support, encouragement and feedback of Dr. Julia Compton, Head of CoSAI and the administrative support of CoSAI's Deputy Head, David Shearer.

Conflict of interest

RK was employed by Strategy and Scale LLC.

Publisher's note

References

Barrett, C., Benton, T. G., Cooper, K. A., Fanzo, J., Gandhi, R., Herrero, M., et al. (2020). Bundling innovations to transform agri-food systems. *Nat. Sustain.* 3, 974–976. doi: 10.1038/s41893-020-00661-8

Butler, C. (2021). *CIP Discussion: Agricultural Innovation, the Key for Bridging RandD with Impact at Scale.* Available online at: https://www.ifpri.org/blog/cip-discussion-agricultural-innovation-key-bridging-rd-impact-scale (accessed September 14, 2022).

Chang, A. M. (2018). *Lean Impact: How to Innovate for Radically Greater Social Good.* Hoboken, NJ: Wiley.

Chiodi Bachion, L., Barcellos Antoniazzi, L., Rocha Junior, A., Chamma, A., Barretto, A., Safanelli, J. L., et al. (2022). *Investigating Pathways for Agricultural Innovation at Scale: Case Studies from Brazil.* Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://wle.cgiar.org/cosai/sites/default/files/CoSAI_IPS_Brazil_final_0.pdf (accessed September 14, 2022).

Chivasa, W., Worku, M., Teklewold, A., Setimela, P., Gethi, J., Magorokosho, C., et al. (2022). Maize varietal replacement in Eastern and Southern Africa: bottlenecks, drivers and strategies for improvement. *Glob. Food Sec.* 32, 100589. doi: 10.1016/j.gfs.2021.100589

Cooley, L., and Kohl, R. (2005). *Scaling Up – From Vision to Large-Scale Change: A Management Framework for Practitioners*, 1st ed. Washington, DC: Management Systems International.

Cooley, L., Kohl, R., and Ved, R. (2016). *Scaling Up – From Vision to Large-Scale Change: A Management Framework for Practitioners*, 3rd ed. Washington, DC: Management Systems International. Available online at: https://msiworldwide.com/sites/default/files/additional-resources/2018-11/ScalingUp_3rdEdition.pdf (accessed September 14, 2022).

Coury, J., Schneider, J. L., Rivelli, J. S., Petrik, A. F., Seibel, E., D'Agostini, B., et al. (2017). Applying the Plan-Do-Study-Act (PDSA) approach to a large pragmatic study involving safety net clinics. *BMC Health Serv. Res.* 17, 411. doi: 10.1186/s12913-017-2364-3

Draper Richard Kaplans Foundation (2022). *A Time to be Even Bolder: 2020–21 Annual Report.* Available online at: https://www.drkfoundation.org/wp-content/

uploads/2022/01/DRK-Annual-Report-2020-21-FINAL.pdf (accessed September 14, 2022).

FAO (2020). Ten *years of the Ethiopian Agricultural Transformation Agency*. Rome: FAO.

FAO (2021). *A Report on the Indicators Under FAO Custodianship: Tracking Progress on Food and Agriculture-Related SDG Indicators 2021*. Available online at: https://www.fao.org/sdg-progress-report/en/ (accessed September 14, 2022).

Foran, T., Butler, J. R. A., Williams, L. J., Wanjura, W. J., Hall, A., Carter, L., et al. (2014). Taking complexity in food systems seriously: an interdisciplinary analysis. *World Dev.* 61, 85–101. doi: 10.1016/j.worlddev.2014.03.023

Foy, C. (2017). *Scaling up of improved poultry breeds in Uganda. Review of successful scaling of agricultural technologies. Produced for the United States Agency for International Development by Management Systems International, a Tetra Tech company, for the E3 Analytics and Evaluation Project*. Available online at: https://www.agrilinks.org/sites/default/files/resource/files/BFS%20Scaling%20Review%20-%20Uganda%20Report%202-13-17%20508%20Final.pdf (accessed September 14, 2022).

Foy, C., and Wafula, M. (2016). *Scaling up of Hermetic Bag Technology (PICS) In Kenya. Review of Successful Scaling of Agricultural Technologies. Produced for the United States Agency for International Development by Management Systems International, a Tetra Tech company, for the E3 Analytics and Evaluation Project*. Available online at: https://agrilinks.org/sites/default/files/resource/files/BFS%20Scaling%20Review%20-%20Kenya%20Report%20REVISED%20508%2011-16-16.pdf (accessed September 14, 2022).

Gage, D. (2012). The venture capital secret: 3 out of 4 start-ups fail. *Wall Street Journal*, Sept. 20.

Hartmann, A., and Linn, J. F. (2007). *Scaling Up: A Path to Effective Development. 2020 Focus Brief on the World's Poor and Hungry People*. Washington, DC: International Food Policy Research Institute. Available online at: https://hdl.handle.net/10625/37196 (accessed September 14, 2022).

Hubeau, M., Marchand, F., Coteur, I., Mondelaers, K., Debruyne, L., and Van Huylenbroeck, G. (2017). A new agri-food systems sustainability approach to identify shared transformation pathways towards sustainability. *Ecol. Econ.* 131, 52–63. doi: 10.1016/j.ecolecon.2016.08.019

International Development Innovation Alliance (IDIA) (2017). *Insights on Scaling Innovation*, 7. Available online at: https://static1.squarespace.com/static/6295f2360cd56b026c257790/t/62a1d43829d380213485d4f9/1654772794246/Scaling$+$innovation.pdf (accessed 4 February 2023).

International Development Innovation Alliance (IDIA) (n.d.). *Why Innovation?*. IDIA. Available online at: https://www.idiainnovation.org/why-innovation#:$%7Bsim%20%7D$:text=What%20is%20Innovation%3F,transformative%20ability%20to%20accelerate%20impact (accessed February 4, 2023).

Jacobs, F., Ubels, J., and Woltering, L. (2018). *The Scaling Scan: A Practical Tool to Determine the Strengths and Weaknesses of Your Scaling Ambition.* Rotterdam: PPPLab; Texcoco, Mexico: International Maize and Wheat Improvement Center (CIMMYT). Available online at: https://repository.cimmyt.org/handle/10883/20505 (accessed September 14, 2022).

Khan, N., Ray R. L., Kassem H. S., Hussain S., Zhang S., Khayyam M., et al. (2021). Potential role of technology innovation in transformation of sustainable food systems: a review. *Agriculture* 11, 984. doi: 10.3390/agriculture11100984

Khandelwal, A., Agarwal, N., Jain, B., Gupta, D., John, A. T. (2022). *Investigating Pathways for Agricultural Innovation at Scale: Case Studies from India.* Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://wle.cgiar.org/cosai/sites/default/files/CoSAI_IPS_India_final_0.pdf (accessed September 14, 2022).

Klerkx, L., and Begemann, S. (2020). Supporting food systems transformation: the what, why, who, where and how of mission-oriented agricultural innovation systems. *Agric. Syst.* 184, 102901. doi: 10.1016/j.agsy.2020.102901

Klerkx, L., and Gildemacher, P. (2012). *Thematic Note 4. The Role of Innovation Brokers in Agricultural Innovation Systems*. Available online at: http://www.bibalex.org/search4dev/files/417999/363989.pdf (accessed September 14, 2022).

Klerkx, L., Hall, A., and Leeuwis, C. (2009). Strengthening agricultural innovation capacity: are innovation brokers the answer? *Int. J. Agric. Resour. Gov. Ecol.* 8, 409–438. doi: 10.1504/IJARGE.2009.032643

Koerner, J., and Duda, A. (2021). *Transformative End-to-end Innovation (E2EI) in a New Era for Food and Climate: Insights and Key Actions Supporting Institutional Change*. CCAFS Info Note. Wageningen: CGIAR Research Program on Climate Change, Agriculture and Food Security.

Kohl, R. (2016a). *Scaling up of Drought Tolerant Maize in Zambia. Review of Successful Scaling of Agricultural Technologies. Produced for the United States Agency for International Development by Management Systems International, a Tetra Tech company, for the E3 Analytics and Evaluation Project*. Available online at: https://agrilinks.org/sites/default/files/resource/files/BFS%20Scaling%20Review%20-%20Zambia%20Report%20REVISED%202-8-16.pdf (accessed September 14, 2022).

Kohl, R. (2016b). *Scaling up of Agricultural Machinery in Bangladesh. Review of Successful Scaling of Agricultural Technologies. Produced for the United States Agency for International Development by Management Systems International, a Tetra Tech company, for the E3 Analytics and Evaluation Project*. Available online at: https://agrilinks.org/sites/default/files/resource/files/BFS%20Scaling%20Review%20-%20Bangladesh%20Report%20FINAL%20508.pdf (accessed September 14, 2022).

Kohl, R. (2016c). *Scaling up of Sahel Rice Varieties in Senegal. Review of Successful Scaling of Agricultural Technologies. Produced for the United States Agency for International Development by Management Systems International, a Tetra Tech company, for the E3 Analytics and Evaluation Project*. Available online at: https://www.agrilinks.org/sites/default/files/resource/files/BFS%20Scaling%20Review%20-%20Senegal%20Report%20FINAL%20508%2011-6-16.PDF (accessed September 14, 2022).

Kohl, R. (2018). *Guide to the Agricultural Scalability Assessment Tool. For Assessing and Improving the Scaling Potential of Agricultural Technologies. Produced Under Contract for US Agency for International Development, E3 Analytics and Evaluation Project*. Available online at: https://agrilinks.org/sites/default/files/resources/asat_guide_revised_508_6-7-18.pdf (accessed September 14, 2022).

Kohl, R. (2022). *Supporting Innovation Pathways for Sustainable Agriculture Intensification: Lessons from Cross Country Evidence*. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/119680 (accessed September 14, 2022).

Kohl, R., and Linn, J. (2021). *Scaling principles. Paper prepared for the Scaling Community of Practice*. Available online at: https://www.scalingcommunityofpractice.com/wp-content/uploads/bp-attachments/8991/Scaling-Principles-Paper-final-13-Dec-21.pdf (accessed September 14, 2022).

LaMorte, W. W. (2022). *Diffusion of Innovation. Behavior Change Modification*. Boston University School of Public Health. Available online at: https://sphweb.bumc.bu.edu/otlt/mph-modules/sb/behavioralchangetheories/behavioralchangetheories4.html#:$\sim$:text=Diffusion%20of%20Innovation%20(DOI)%20Theoryspecific%20population%20or%20social%20system (accessed February 4, 2023).

Linn, J. (2022). Three *Case Studies: Applying the Scaling Principles of the Scaling Community of Practice*. Available online at: https://www.scalingcommunityofpractice.com/three-case-studies-applying-the-scaling-principles-of-the-scaling-community-of-practice (accessed September 14, 2022).

Mati, B. M., Sijali, I. V., and Ngeera, K. A. (2022). *Investigating Pathways for Agricultural Innovation at Scale: Case Studies from Kenya*. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://wle.cgiar.org/cosai/sites/default/files/CoSAI_IPS_Kenya_final_0.pdf (accessed September 14, 2022).

Minh, T. T., Schmitter, P., and Smith, M. (2021). *Adaptive Scaling to Achieve System Transformation in One CGIAR*. Technical Brief. International Water Management Institute. Available online at: https://cgspace.cgiar.org/bitstream/handle/10568/113924/Adaptive%20scaling%20to%20achieve%20system%20transformation%20in%20One%20CGIAR.pdf (accessed September 14, 2022).

OECD (2022). *Government Support to Agriculture is Increasing*. Organisation for Economic Co-operation and Development. Available online at: https://www.oecd.org/agriculture/topics/agricultural-policy-monitoring/government-support-to-agriculture-is-increasing.htm (accessed September 14, 2022).

Pretty, J., Toulmin, C., and Williams, S. (2011). Sustainable intensification in African agriculture. *Int. J. Agric. Sustain.* 9, 5–24. doi: 10.3763/ijas.2010.0583

Rogers, E. (2003). *Diffusion of Innovations*, 5th ed. New York, NY: The Free Press.

Saldanha, L. (2019). Budget push for zero budget farming but contradictions mar Andhra's natural agri foray. *Down to Earth*. 9 July. Available online at: https://www.downtoearth.org.in/news/agriculture/budget-push-for-zero-budget-farming-but-contradictions-mar-andhra-s-natural-agri-foray-65503 (accessed September 14, 2022).

Seelos, C. (2020). Changing systems? Welcome to the slow movement. *Stanf. Soc. Innov. Rev.* 18, 40–47.

Seelos, C., Farley, S., and Rose, A. L. (2021). *The 'Thou Shalt Nots' of Systems Change*. Stanford Social Innovation Review. 14 January. Available online at: https://ssir.org/articles/entry/the_thou_shalt_nots_of_systems_change (accessed September 14, 2022).

Shilombenia, H., Owaygen M., De Plaen, R., Manchur, W., and Husak, L. (2019). Scaling up innovations in smallholder agriculture: lessons from the Canadian international food security research fund. *Agric. Syst.* 175, 58–65. doi: 10.1016/j.agsy.2019.05.012

Simmons, R., Ghiron, L., and Fajans, P. (2021). The Evidence to Action project's scale-up synthesis webinar: questions and answers with scale-up experts. *ExpandNet*. Available online at: https://expandnet.net/wp-content/uploads/2021/08/2020-E2A-Scale-up-Synthesis-Webinar-Q-and-A-responses.pdf (accessed September 14, 2022).

SoPact (). *Venture Philanthropy: Comprehensive Venture Philanthropy Guide*. Available online at: https://www.sopact.com/venture-philanthropy (accessed September 14, 2022).

Starr, K. (2021). We're beating systems change to death. *Stanford Social Innovation Review*. 8.

WHO and ExpandNet (2010). Nine *Steps for Developing a Scaling-up Strategy*. Geneva: World Health Organization. Available online at: https://hdl.handle.net/10665/44432 (accessed September 14, 2022).

Woltering, L., Fehlenberg, K., Gerard, B., Ubels, J., and Cooley, L. (2019). Scaling – from "reaching many" to sustainable systems change at scale: a critical shift in mindset. *Agric. Syst.* 176, 102652. doi: 10.1016/j.agsy.2019.102652

World Bank (2012). *Agricultural Innovation Systems: An Investment Sourcebook*. Washington, DC: World Bank.

World Bank (2019). *Agricultural Innovation and Technology Hold Key to Poverty Reduction in Developing Countries, Says World Bank report, September 16, 2019*. Available online at: https://www.worldbank.org/en/news/press-release/2019/09/16/agricultural-innovation-technology-hold-key-to-poverty-reduction-in-developing-countries-says-world-bank-report (accessed September 14, 2022).

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 09 May 2023
DOI 10.3389/fsufs.2023.1108949

Check for updates

OPEN ACCESS

EDITED BY
Ademola Braimoh,
World Bank Group, United States

REVIEWED BY
Sunday Agbeniyi,
Cocoa Research Institute of Nigeria (CRIN), Nigeria
David Simon,
Royal Holloway, University of London, United Kingdom

*CORRESPONDENCE
P. V. Vara Prasad
vara@ksu.edu

†PRESENT ADDRESSES
Ruben Echeverría,
Bill & Melinda Gates Foundation, Seattle, WA, United States

Nienke Beintema,
Wageningen Centre for Development Innovation, Wageningen, Netherlands

Julia Compton,
Independent Researcher and Consultant, Cardiff, United Kingdom

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 26 November 2022
ACCEPTED 23 February 2023
PUBLISHED 09 May 2023

CITATION
Prasad PVV, Bhatnagar N, Bhandari V, Jacob G, Narayan K, Echeverría R, Beintema N, Farah Cox P and Compton J (2023) Patterns of investment in agricultural research and innovation for the Global South, with a focus on sustainable agricultural intensification. *Front. Sustain. Food Syst.* 7:1108949. doi: 10.3389/fsufs.2023.1108949

Patterns of investment in agricultural research and innovation for the Global South, with a focus on sustainable agricultural intensification

P. V. Vara Prasad[1]*, Nirat Bhatnagar[2], Vineet Bhandari[2], George Jacob[2], Kaushal Narayan[2], Ruben Echeverría[3†], Nienke Beintema[3†], Paul Farah Cox[4] and Julia Compton[3†]

[1]Sustainable Intensification Innovation Lab, Kansas State University, Manhattan, KS, United States, [2]Dalberg Advisors, New Delhi, India, [3]Commission on Sustainable Agriculture Intensification, International Water Management Institute, Colombo, Sri Lanka, [4]Scriptoria, London, United Kingdom

This study is the first attempt to determine global investment patterns for research and innovation in agriculture systems for the Global South, and specifically for innovation funding targeted at sustainable agricultural intensification. We analyzed and modeled patterns of funding from governments in the Global South, development partners, private companies, and private equity and venture capital funds, using primary and secondary sources of data spanning 2010 to 2019. We ascertain the key providers and recipients of innovation funding and how it is shared out between different topics and value chains. Results showed that about $60 billion of funding (ranging from $50 to $70 billion) goes toward agricultural innovation for the Global South each year, with 60–70% of it coming from these countries' own governments (and the government of China accounting for as much as all others combined). This $60 billion investment represents just 4.5% of Global South agricultural output. Furthermore, <7% of the total funding was found to have detectable environmental intentions, and less than 5% had both social and environmental intentions. Adopting a standard for transparent reporting and measurement could potentially lead to swift changes in funding patterns toward sustainability goals.

KEYWORDS

innovation, investments, agriculture, sustainable intensification, Global South, research

1. Introduction

The countries of the Global South face monumental agricultural challenges in the coming decades. They will have an estimated 31% more people to feed by 2050—which will be around 86% of the world population (United Nations, 2022). The total population in the Global South will put severe constraints on resources and carbon budgets. For instance, China will face the daunting task of feeding 22% of the world population with 7% of the world's arable land (Chaudhury, 2020), while India will need to feed 20–25% of the world's population with only 4% of the world's freshwater (World Bank, 2022). However, in year 2022, the rate of population increase declined in China and population decreased for the first time over many decades, and this trend may continue. While population of India will continue to rise although at slightly slower rates. Additionally, adequate livelihoods will need to be found for millions living in rural areas who will face shrinking land sizes and incomes. Significant innovation in sustainable agricultural intensification (SAI) will be necessary to meet food demand while avoiding environmental and socio-economic disaster (Steensland, 2021).

A thorough understanding of funding trends in agricultural research and innovation (hereafter shortened to "innovation") is critical to guide future funding decisions and help in the sustainable achievement of food goals. However, funding data were scattered, definitions of sustainability and innovation were not consistently applied by different actors, and consequently, a global view of these funding patterns is missing. While many stakeholders within the agricultural innovation system align on the need to switch to sustainable agricultural practices and on the need for increased funding on this topic, further effort is hindered due to a poor understanding of the current funding patterns for innovation. While there have been some successful efforts to track funding for agricultural research (for example Dehmer et al., 2019; OECD, 2019; Beintema et al., 2020) this is mainly focused on science and technology and there is little or no information available on other important aspects of innovation, for example in finance and business practices (FAO, 2022). Moreover, global data are fragmented and not based on a common framework and definitions. Consequently private, public and philanthropic investors in innovation might be trading off sustainability in the future for short- to medium-term gains in agricultural productivity using unsustainable methods. Further, even wellintentioned stakeholders and investors might be underfunding in SAI innovation or might have a misplaced assessment of sectors and themes that need more funding.

Such is the backdrop for this effort to reach a baseline estimation of SAI innovation funding intended for the Global South. This article outlines the key findings from a working paper (Dalberg Asia, 2021a) commissioned by the Commission on Sustainable Agriculture Intensification (CoSAI; https://www.iwmi.cgiar.org/archive/cosai/), an independent international commission supported by Consultative Group for International Agricultural Research (CGIAR), a global agrifood research network. The assessment covers funding into different categories of SAI innovation activity, globally, by the public sector, private sector, philanthropic and development donors, as well as and private equity and venture capital[1] (PE/VC). We assess the total funding being made annually into agricultural innovation by these actors; the total funding being made in SAI innovation as a subset of agricultural innovation; and how this funding is split between regions, value chains and categories of innovation. Our findings present an opportunity for future updates to revise these estimates as new data becomes available.

2. Materials and methods

Full details of the methodology can be found in Dalberg Asia (2021b). The study covers the 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 (Figure 1). Data spanning 2010–2019 was collected from industry reports; annual reports of companies; government budget and funding documents; third-party online funding data sources such as Tracxn.com and Statista.com (PE/VC), OECD.Stat (development partners) and the Bill and Melinda Gates Foundation (BMGF) grants database (BMGF, 2020); expert conversations; and credible media reports. Individual framework of analysis for funding streams or projects were identified to the extent possible, and each was tagged by innovation layer (Figure 2), value chain, funding source, funding recipient, target country, and SAI domain (see definitions below). Other tags (e.g., funding instrument, stage of innovation, target user type) were also applied where information was available, but results are not presented for these as the data were too patchy. Tagging was done manually for most data, with sampled cross-checking, but for the OECD. Stat dataset, given its size, we used word crawl algorithms along with sampled triangulation.

Once tagging was complete, we summed individual funding streams to estimate total funding and share by category. For several questions, funding data lacked comprehensiveness or granularity, and the models developed for this study use extrapolations and interpolations to compute funding values in these cases. The results highlight ranges and assumptions wherever appropriate. The reasonableness of the estimates was validated, where possible, through experts across each of the funder categories.

All values were converted to constant 2019 prices and constant 2019 US$ exchange rates. Comparisons across countries will thus differ from calculations based on purchasing power parity, such as Beintema and Stads (2019).

2.1. Definitions used for the analysis

Funding in innovation, agriculture, SAI and the Global South are constructs interpreted differently by different organizations. This study used the following definitions.

2.1.1. Funding in innovation

This includes all funding related to the creation or adoption of new agricultural technologies, practices and systems (Table 1). 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,

1 Private equity (PE) refers to funding from institutional and/or individual investors in return for an equity stake in potentially high-growth investments and companies not quoted on a stock exchange. Venture capital (VC) is a subset of PE that supports early-stage, high potential start-ups, taking higher investment risks and seeking commensurate returns.

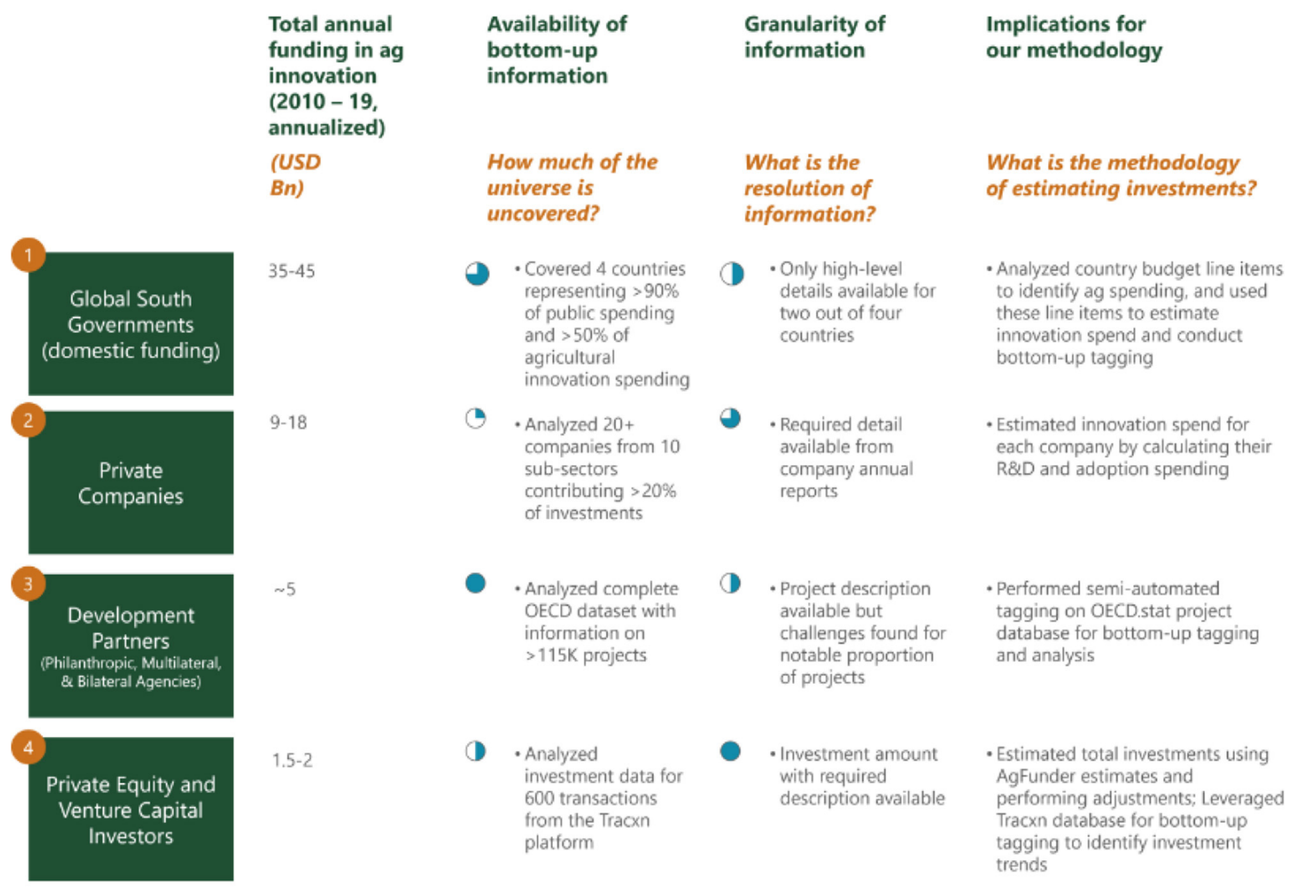


FIGURE 1
Data availability and granularity across different funding sources. Source: Dalberg Asia (2021a).

and marketing funding on innovative technologies. This expanded definition allows the study to count new business models, startup funding on e-commerce platforms that promote access to agriculture inputs, and other similar examples—all important funding in agricultural innovation. On the other hand, pure subsidies to purchase existing products and services in agriculture, routine administration costs, and general infrastructure funding such as rural roads are not counted as innovation funding. Percentage values for funding other than research and development (R&D) were applied to individual funding streams on a case-by-case basis to account for funding that was judged to support adoption of innovative agricultural practices. All percentages used are listed in the detailed methodology (Dalberg Asia, 2021b).

2.1.2. Agriculture

The study includes all funding linked to on-farm food value chain activities and any off-farm processes essential to the production of a consumable food product. Since the goal of the study is to understand the Global South's preparedness for a sustainable food secure future, the analysis is limited to funding in food, including, for example, innovations related to on-farm food production, milling, milk pasteurization and urban/vertical farming. It excludes funding in cash crops such as cannabis, cotton, paper, rubber and wood, as well as innovations for food retail and in non-essential value-added categories such as milk flavoring or manufacturing of potato chips. It also excludes innovation in general areas that have indirect effects in agriculture: for example, innovation in general information technology is excluded but innovation in applications for agricultural extension or finance would be included.

2.1.3. Sustainable agricultural intensification (SAI)

It is a multi-dimensional construct with different actors adopting different definitions (e.g., Pretty, 1997; Garnett et al., 2013; Rockström et al., 2017; Mockshell and Kamanda, 2018). This study uses five agriculture sustainability domains—economic, social, environmental, human condition, and productivity—laid out in the Sustainability Intensification Assessment Framework by Musumba et al. (2017) and Stewart et al. (2018) (web version of the framework available at https://sitoolkit.com). This framework was used since it allowed the team to analyze funder intentions with variable quality data across multiple funders, while providing the flexibility to consider various definitions of SAI.

We tagged stated SAI intentions for each sustainability domain for each individual research/innovation project or funding stream analyzed, based on its title and any other description or keywords available. Examples are given in Table 2. We define both a broad (minimum requirements) and a narrow (more demanding)

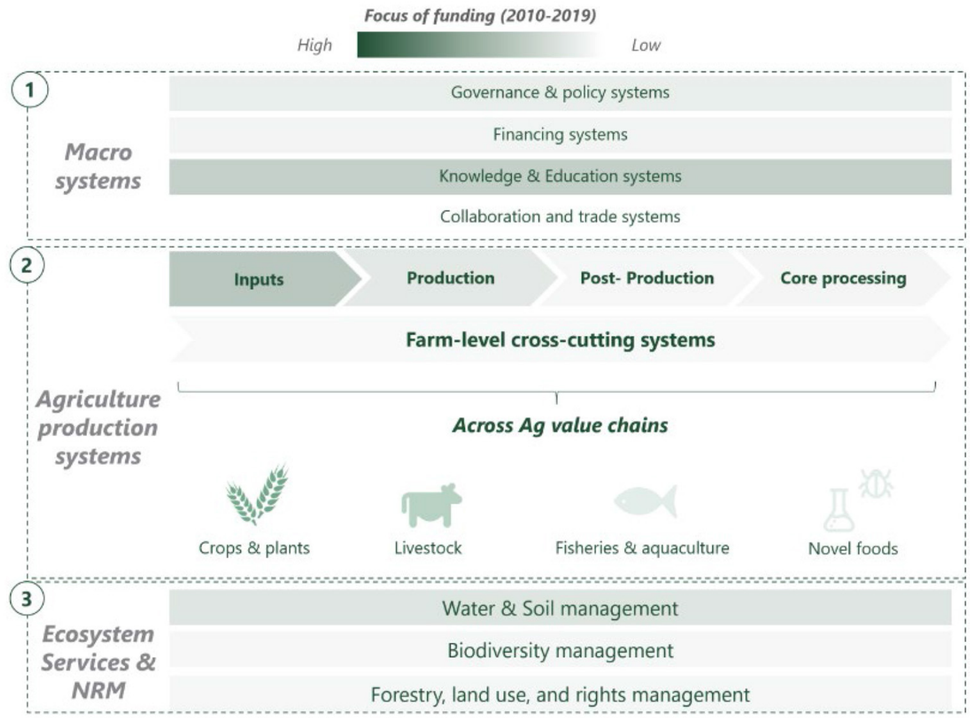


FIGURE 2
Framework of analysis for innovation funding. Source: Dalberg Asia (2021a).

TABLE 1 Funding for innovation in agriculture: what the study included.

	Funding type	Proportion considered	Example of inclusions
1	Research and development (R&D)	100%	Research and product development funding to develop a new seed variety
2	Extension/marketing	% Depending on funding description	Programs training farmers on using new agroforestry practices; Marketing spends for a new hybrid seed
3	Institutional/infrastructure		Management and maintenance of research institutions; Operations of programs to modernize slaughterhouses
4	Policy reform		Funding in implementation or adoption of agricultural policies, e.g., reform of fertilizer subsidies
5	Process/business model changes		PE/VC funding for startups developing digital marketplaces for purchase and sale of agricultural produce

Source: Dalberg Asia (2021a).

meaning of SAI (Figure 3), and report results according to the broad definition, except where otherwise noted:

- *Broad definition of SAI:* Funding that intends to produce both gains in productivity and improve environmental sustainability.
- *Narrow definition of SAI:* Funding that meets the above criteria, and also intends to improve human (nutrition, education) *or* social (equity) dimensions, as shown in Figure 3.

2.1.4. The Global South

This term used in this report follows the World Bank classification of low- and middle-income countries, which includes countries and territories in Asia (including China but excluding Japan, Singapore, and South Korea), Central America, South America, Mexico, Africa (including South Africa), and the Middle East (excluding Israel). Further, this study looks at funding targeted "for" the Global South. This means that it considers innovations intended to specifically impact Global South nations. However, for two funding sources—governments and PE/VC investors—this study looks at funding "in" the Global South nations, since based on expert interviews, this seems a suitable proxy for funding for the Global South. For example, most funding for agricultural research in Kenya is focused on Kenya or other Global South nations.

2.2. Limitations of the study

The estimates in this study have many sources of uncertainty. Data on agricultural innovation funding, especially SAI innovation,

TABLE 2 Examples of stated intentions considered under each sustainability domain.

Economic	Environment	Social	Human	Productivity
Increasing output per unit input	Improved soil quality	Social equity	Improved nutrition	Improving yields
Reducing variability of profit	Improved biodiversity	Gender equity	Health and food safety	
Reducing cost of production	Improved water quality	Reduced conflict	Food security	
	Mitigation of climate change		Improved capacity to learn	
	Reduction of ocean acidification			
	Fuel availability			
	Biogeochemical flows			

Source: Dalberg Asia (2021a). Domains based on Stewart et al. (2018) (www.sitoolkit.com).

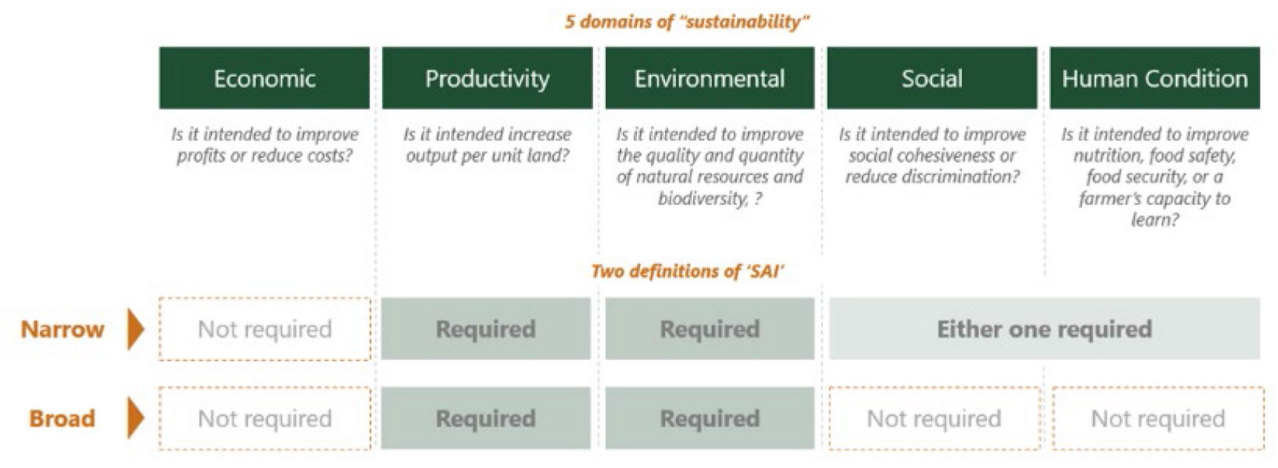


FIGURE 3
Broad and narrow definitions of sustainable agricultural intensification (SAI) based on stated intentions. Source: Dalberg Asia (2021a). Five domains of sustainability based on Stewart et al. (2018) (www.sitoolkit.com).

is not easily accessible, and few countries or organizations report this data in sufficient detail. Since many of the specific analyses in this report are, to the best of our knowledge, being carried out for the first time, they incorporate assumptions and extrapolations based on the best information we could obtain, including expert opinion. Specific assumptions, multipliers and sources are fully listed in the detailed methodology (Dalberg Asia, 2021b).

The study extrapolated global funding from the sum of the largest funders, especially for public and private sector funding. Detailed data were not obtained for any but the largest private investors and countries. This led to two major limitations: the global analysis could not be disaggregated (e.g., by continent), and the analysis was potentially biased by those included: in particular, detailed country data on SAI investment was limited to India, and some food companies were excluded (FAO, 2022). Pray and Fuglie (2015) expertly discuss the challenges with estimating private sector funding for agricultural R&D. The development partners category excludes funding not captured by the Organization for Economic Co-operation and Development (OECD). Stat database, for example public research funding provided by the Global North but not counted as Official Development Assistance (ODA); funding not marked as research or innovation; and some philanthropic and multilateral funders that do not report details of their projects within the OECD Creditor Reporting System—but this is a less important limitation.

As in some similar studies of funding flows (Biovision and IPES Food, 2020), our analysis of SAI funding is based on stated sustainability *intention*, not the finally-achieved outcomes (and impacts), for which data were very rarely available due to long lags between investment and outcomes at scale (Frontier Economics, 2014; Rijsberman, 2016; FAO, 2022), as well as the challenge of attributing outcomes to specific innovations (Maredia et al., 2014). This is an important limitation of the study that may lead to over- or under-estimating SAI outcomes in individual cases—but without better data, it is not easy to tell whether there is a consistent overall bias. Stated "good intentions" may over-estimate SAI outcomes in many cases, not only because of potential greenwashing (Gatti et al., 2019) but because of the inherently risky and long-term nature of research and innovation. Equally, stated intentions may underestimate SAI outcomes when increased productivity alone has positive effects on sustainability outcomes such as poverty, nutrition or climate change mitigation (Searchinger et al., 2019; Fuglie et al., 2022).

Furthermore, as the study relies on project or program funding descriptions to identify SAI intentions, there are likely to be underestimates due to inadequate descriptions. Underestimation is potentially more likely in the case of Global South governments, which are under less pressure to describe their innovation programs as sustainable than are development partners and large-scale private sector companies. On the other hand, in some cases, particularly for private corporations, SAI tagging was applied to large areas of funding when more granular data were not available (e.g., using annual reports), and this may have overstated specific intentions for individual projects and funding streams.

This data did not allow us to distinguish between different degrees of sustainability, or between "incremental" and "transformational" innovation (Gliessman, 2015). For example, a piece of research on precision application of pesticides (to reduce the quantity applied) would be identified as "environmentally sustainable intentions," i.e., the same as an agroecological investment. This is a limitation of this study which can only be fixed in future by broad agreement on definitions and improving reporting standards.

Finally, our analysis measures *external funding* into innovation and not cash or labor investments made by farmers or other direct value chain actors in their own enterprises, although this is recognized to be globally important (MacMillan and Benton, 2014; Waters-Bayer et al., 2015).

3. Results

Here we examine the main patterns of funding in agricultural innovation for the Global South over the period 2010–2019, and the allocation of these funds across funding sources, implementing agencies, and sub-sectors and value chains within agriculture.

We estimated average total annual funding on agricultural research and innovation for the Global South between 2010 and 2019 to be about $60 billion per year (range $50–70 billion). This total represents just 4.5% of agricultural output value in the Global South (as sourced from FAO.Stat datasets on agricultural value-added, constant US$). This innovation funding intensity compares poorly to the energy sector, another critical sector for economic growth and tackling climate change, which has sub-sectors spending 6% of revenue on R&D alone (and significantly higher if other innovation cost heads, such as marketing the innovation, are considered) (Osborne, 2019). If an equivalent ratio (6%) were applied to the agriculture sector, this would imply a non-trivial increase of about $20 billion a year in innovation funding for the Global South.

Over the decade examined (2010–2019), overall funding in agricultural innovation increased. The first half of the decade saw substantial growth averaging ~7% per annum, driven primarily by increases in government as well as private sector funding. However, large private sector investment in innovation decelerated to 2% per year in the second half of the decade, as discussed below.

R&D as traditionally understood—i.e., conducting scientific research or developing new technical products and services—accounted for just 33% of total innovation funding. Marketing of technical innovations (a fraction of overall marketing funding by organizations), along with public and private sector extension services and training programs to help farmers and producers adopt these innovations, accounted for 37%. Innovations that intend to create or strengthen institutions or infrastructure accounted for another 26%—for instance, programs such as the Rashtriya Krishi Vikas Yojana (https://rkvy.nic.in) and National Horticulture Missions (https://hortnet.gov.in) in India. Innovation funding for new policies and subsidies for adoption of innovations only accounted for only a small fraction of the overall funding spend (<5%), although it was possible that some policy funding was counted under other types of innovation. Increased funding for policy innovation, as well as bundling policy and institutional reform with technical innovation (Barrett et al., 2020), could drive sustainability transformation at scale. For example, in Brazil, EMBRAPA (The Brazilian Agricultural Research Corporation) has worked closely with the government to develop agricultural policies that enable productivity and sustainability within the sector (see Dalberg Asia, 2021c), and CGIAR also works extensively with policy-makers (Njuki and Nicol, 2021).

3.1. Main funding sources, value chains, and recipients

The main patterns of funding are shown in Figure 4. Using $60 billion as the denominator, Global South governments account for about 60–70% of total innovation funding; the private sector about 15–30%; development partners (multilateral development banks, bilateral aid agencies and philanthropic foundations) about 8%; and startups funded by PE/VC 2–3% of the total.

Funding for innovation in food commodity value chains increased (both real terms and percentage) by about 50% over the decade examined (Figure 5). Crops received 50–60% of value chain-related funding, with livestock <20% and fisheries and aquaculture about 5%. Crops account for 80–90% of the cumulative innovation funding made by the private sector and startups, largely due to innovation programs at large seed, pesticide and fertilizer companies such as Bayer Crop Science, ChemChina, Syngenta and John Deere (farm equipment for crops) that invest significantly in both R&D and marketing of innovations.

Overall, the innovation funding in crops from the private sector is higher than their proportionate contribution to overall output value (Figure 6). However, innovation funding for both fisheries and livestock are expected to increase significantly in the future due to the high commercial value of these categories. A higher focus on sustainability will be important given the high environmental footprints, especially for livestock (Herrero et al., 2015) and aquaculture. We found a significant increase in funding (both real terms and percentage) for fisheries and livestock in PE/VC funding to agricultural innovation over the decade (from a low base): livestock and fisheries received only about 1% of funding in 2010, but this had increased to close to 10% by 2019.

While funding for alternative proteins still forms a small fraction of overall funding in agricultural innovation, this is growing very rapidly in the Global South, as it is globally (Dion et al., 2020; FAIRR, 2021), and if successful models and products emerge, some innovation funding from livestock and fisheries might get redirected to this space.

The main recipients (users) of agricultural innovation funding are government agencies (~50%) and private companies (~30%); universities and research institutes (~16%), with

FIGURE 4
Flow of funds by source and recipient of innovation funding 2010–2019 (annualized, constant 2019 prices). Source: Dalberg Asia (2021a).

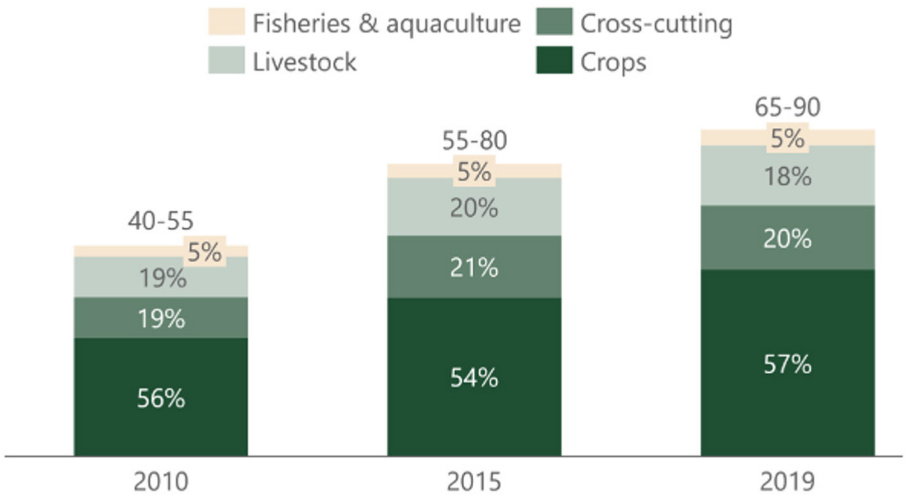


FIGURE 5
Estimated total agricultural innovation funding for the Global South by main value chain in 2010, 2015, and 2019 (US$ billion, constant 2019 prices; see text for definition of cross-cutting). Source: Dalberg Asia (2021a).

non-governmental organizations (NGOs) and civil society organizations (CSOs) accounting for <5%. There are clear patterns in funder–recipient pairs for agricultural innovation funding. Governments mostly fund public programs. Similarly, private companies' channel most of their innovation funding back into their own or other private sector firms, with a tiny fraction being directed toward universities and public research institutes—for example, in Brazil, Bayer and Syngenta have both collaborated with the federal research agency, EMBRAPA (Dalberg Asia, 2021c).

3.1.1. Global South governments

Governments are the largest funders of agricultural innovation in the Global South, accounting for about $40 billion (range $35–45 billion), or about two thirds of the total (Figure 4). This is equivalent to 10–13% of *all* agricultural-related funding by governments in the Global South (using the expenditure on agriculture, forestry and fishing as reported in the FAOSTAT database). Public funding in agriculture innovation is dominated by China, India, and Brazil, with these three governments accounting for nearly 40% of overall agricultural innovation in the Global South (Table 3).

Of the total public funding about 37% goes toward marketing programs and 27% of public funding on agricultural innovation goes toward technology and R&D activities. Science and technology funding in agriculture largely goes to single government apex research institutions that coordinate agricultural research in their respective countries or utilize funding for their own research, with the remaining funds flowing to state level and affiliated agricultural research institutes and universities. Examples of apex research institutions include the Chinese Academy of Agricultural Sciences (CAAS), the Indian Council of Agricultural Research (ICAR), EMBRAPA in Brazil, and the Kenya Agricultural and Livestock Research Organization (KALRO).

Governments, in their enabler role, fund more on innovations to help new products and services get adopted and scale than on R&D to create those new products. An average of 37% of public funding goes toward agricultural extension and training programs, while about 34% goes toward institutional funding, new infrastructure, and agrarian reform. An example from the second category is the dairy entrepreneurship development program in India, which among its other objectives, intends to modernize dairy farms for production of clean milk and bring structural changes in the unorganized sector so that initial processing of milk can be taken up at the village level.

There were, however, striking differences between countries (Figure 7). China alone accounts for approximately half of all Global South government innovation funding in agriculture, followed by Latin American governments (driven by Brazil with 20–30% of regional funding) and South Asian governments (driven by India at 50% of the regional funding). As also noted by Chai et al. (2019), China has overtaken the USA in agricultural R&D on a purchasing power parity basis—and this has been reflected in high agricultural Total Factor Productivity gains in China, of over 3% per year (OECD, 2019).

Government funding increased over the decade examined, consistently driven by China (5% annual growth) and India (9% annual growth). Brazilian government funding on the other hand stayed fairly constant over the period, despite growing agricultural exports and output, even declining slightly after 2014. Some public funding in Brazil has been substituted by innovation funding by large companies such as Bayer and Syngenta, who have funded agricultural research within Brazil in recent years including through prominent collaborations with EMBRAPA (Dalberg Asia, 2021c).

Nearly half (47%) of all innovation funding by governments goes toward crops, but in India this was higher, at nearly 70%. Approximately 27% of funding focuses on cross-cutting themes such as forest preservation, water conservation and general agricultural reforms, especially prominent within countries such as Brazil. Livestock and fisheries receive only 20% of the overall funding on innovation by governments. Compared with the relative output value of crops, governments spend relatively more on crops than livestock and fisheries (Figure 6), perhaps because a majority of the agricultural workforce is employed within the crops value chain.

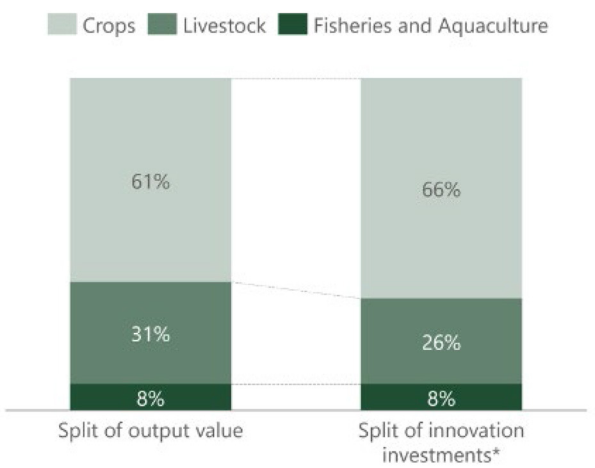


FIGURE 6
Estimated annual funding by private companies for agricultural innovations focused on the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a).

3.1.2. Private corporations

Private corporations funded ∼$13 billion (in the range of $9–18 billion) annually over the last decade on agricultural innovation for the Global South, accumulating to $150 billion (ranging from $90–180 billion), representing 15–25% of the overall agricultural innovation funding for the Global South. The funding is roughly evenly split between R&D funding and non-R&D funding in marketing and adoption support. Key players include agriculture-related divisions of global giants such as Bayer Crop Science, Syngenta and Archer Daniels Midland. While smaller agribusinesses also contribute to innovation in the agriculture and food sector, they have a very small financial contribution compared to the largest global agricultural corporations (see also OECD, 2019).

Farm mechanization (∼25% of total) and pesticides (∼23% of total) represent the largest sub-sectors in terms of innovation funding by the private sector (Figure 8). Funding in these sub-sectors is dominated by large companies including John Deere, Cargill, Bayer Crop Sciences and Syngenta, and focuses predominantly on crops. Other sizable categories include funding from meat and poultry processing companies (∼10%), animal health companies (∼6%), fertilizer companies (∼3%) and commodity-specific processing companies (∼3%), while fisheries and aquaculture are estimated to receive <2% of the total innovation funding. Precision agriculture-related innovation funding forms ∼1% of the total funding by private companies; however, it is the fastest growing category, growing at ∼25% a year in the past decade (as also noted by Fuglie, 2016) for PE/VC spending on precision agriculture).

TABLE 3 Funding in agricultural innovation by Global South governments.

Governments	Total funding in agricultural innovation	% of total govt. funding in agricultural innovation	% of total funding in agricultural innovation
China	$20 bn ($15–25 bn)	48%	33%
India	$3 bn ($2.5–3.5 bn)	7%	5%
Brazil	$2 bn ($1.5–2.5 bn)	5%	3%
Rest of Global South	$17 bn ($15–20 bn)	40%	28%

Source: Dalberg Asia (2021a).

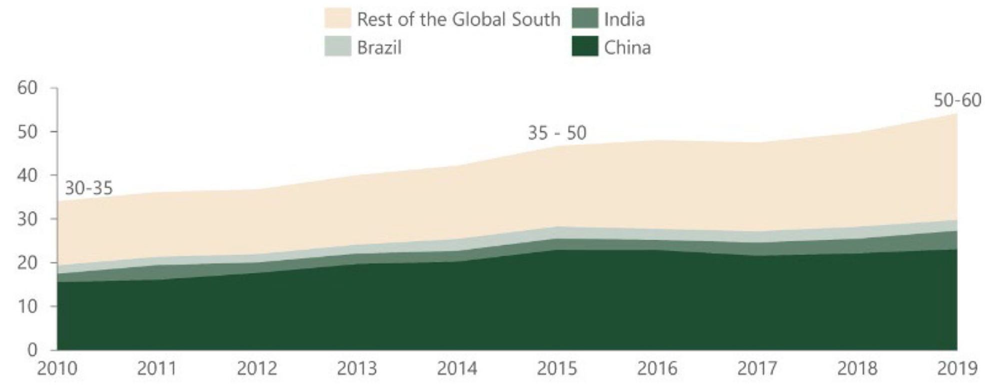


FIGURE 7
Estimated annual government agricultural innovation funding in the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a).

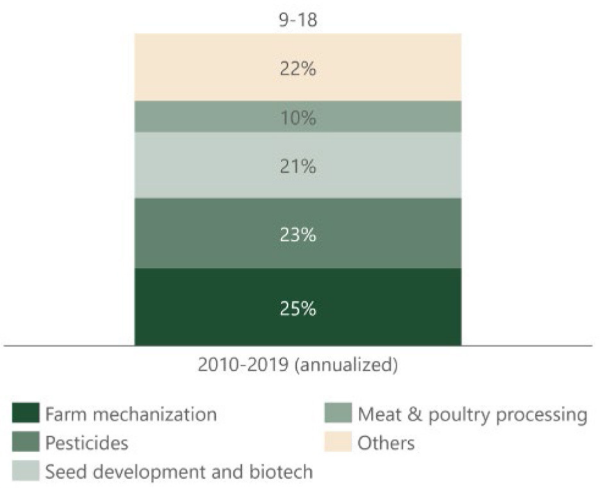


FIGURE 8
Estimated annual funding by private companies for agricultural innovations focused on the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a).

Overall, agribusinesses saw a deceleration of overall innovation growth (to 2% annually) and a slight fall in their R&D intensity ratios (defined as expenditures over sales) over the final years of the decade examined (for instance, Syngenta's R&D intensity fell from 10.1% in 2017 to 6.7% in 2019). The deceleration was most noticeable in large agricultural input companies in sectors such as farm mechanization, seeds development and biotech. According to private sector experts we interviewed, this is likely because agricultural input companies face high costs of innovation due to an increasingly restrictive regulatory environment and increasingly complex next-generation innovations, which together with consumer preferences have pushed these companies to focus on incremental innovations instead of breakthrough ones, calling for a need to de-risk private capital to stimulate transformative innovations (see also Kurth et al., 2020).

3.1.3. Private equity and venture capital investors

PE/VC investors funded $1.3–2 billion per year in agricultural innovation between 2010 and 2019 (Figure 4), accounting for 2–3% of the overall innovation funding in agriculture for the Global South. Although PE/VC funding represents a small share of the overall agricultural innovation funding, a large percentage of this funding is for disruptive innovation that can have an outsized impact if the technologies work and the business models prove viable (Cirera and Maloney, 2017). For example, startups that increase information availability on markets, climate and agronomic recommendations will help smallholder farmers but also put pressure on intermediaries within the value chain, which causes dynamic effects on the way business is conducted in the sector. Another example is startups that create new markets and increased value for byproducts and waste from agriculture.

The thematic analysis (Figure 9) drew from databases that capture granular flow in the PE/VC investors, and then modeled funding for the Global South to count funding into startups, not just in the Global South but also into companies based in the Global North where spillovers are likely (for detailed methods see Dalberg Asia, 2021b). Examples of such spillovers include a German startup, Plantix, which has developed an AI engine to detect pests in crops and has a significant user base in India (GINSEP, 2021). Innovative technology-enabled agri-marketplaces and farmer engagement platforms (offering a combination of information, market linkages and sometimes financial support) received ~60% of all PE/VC agriculture funding, followed distantly by seed development and biotech startups at ~15%. Examples of companies that received funding include Ninjacart (India), Fruitday (China) and Meicai (China), which are all focused on creating tech-based business models that use advanced analytics to drive supply chain efficiencies in agricultural value chains. Examples of seed development companies that received funding included Advanta (India) and Nuziveedu Seeds (India). From a commodity lens in terms of technologies, marketplaces, farmers engagement and biotech, crops attract the highest share of PE/VC funding, although funding that cut across commodity chains also received a notable proportion of funding, driven largely by funding for innovative agricultural financing companies that target both

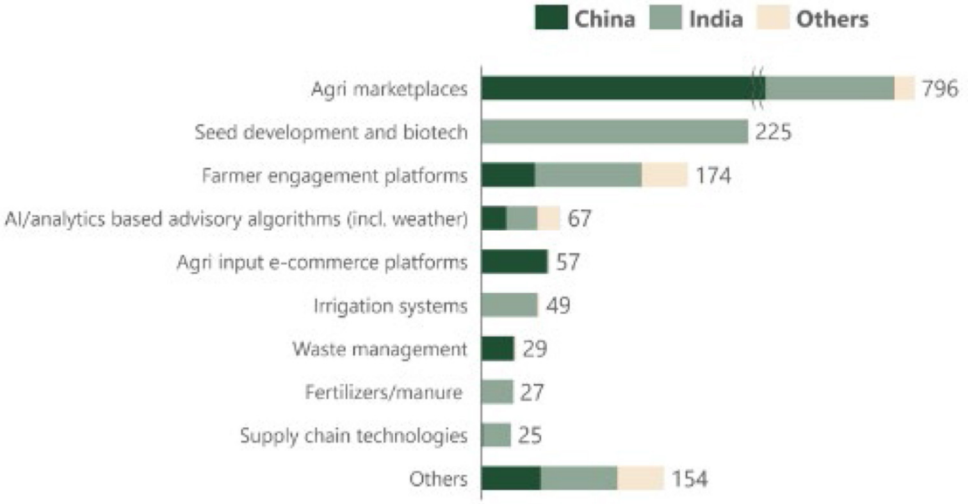


FIGURE 9
Estimated annual innovation funding by private equity and venture capital investors in agriculture-related start-up companies based in the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a) and Tracxn.

individual farmers and agricultural businesses (see Dalberg Asia, 2021d).

China and India are the largest users of PE/VC funding in agriculture (both domestic and international), together accounting for ∼90% of PE/VC agricultural investments, far ahead of Kenya (∼3%), and Nigeria, Brazil, Argentina and Mexico (each about 1% of total).

3.1.4. Philanthropic, multilateral, and bilateral agencies

Based on data from OECD databases, average funding by development partners for agricultural innovation is estimated to be at ∼$6 billion per year between 2010–2019 on average (about 8% of the total).

Funding by development partners is dominated by bilateral agencies (about 70%, although reducing in amount and share over the decade), followed by multilateral grants with about 25%. The USA is the leading bilateral funder, followed by European countries and Japan. While multilateral agencies such as the World Bank's International Development Association (IDA) and the International Fund for Agricultural Development (IFAD) are very important funders of research and innovation, especially in low-income countries, most of their funding takes the form of loans to national governments, which are counted here as national funding. Philanthropic foundations, dominated by the influential BMGF, on average accounted for about 10% of funding by development partners, or about 1% of all agricultural innovation funding for the Global South; however, this notably increased (both real terms and percentage) from <4% of the total in 2010 to 13% in 2019 (Figure 10).

Overall, nearly half (46%) of bilateral and multilateral grants for agricultural innovation was targeted toward sub-Saharan Africa. South Asia and Latin America received about 12% each, followed by other regions. Within South Asia, Afghanistan received ∼50% of all funding for the region, followed by India, Pakistan, Bangladesh and Nepal, which received ∼10–12% each. Nearly two thirds (∼65%) of philanthropic funding goes to sub-Saharan Africa—fairly evenly spread across countries—with other major recipients being in Latin America and Southern Asia (driven by India).

Finally, China and India themselves invest more than $600 million per year (together) in agricultural innovation funding as development partners, also mostly for sub-Saharan Africa. For example, China funds technology demonstration centers in Africa to promote the usage of and train stakeholders on new agricultural technologies to increase production and economic efficiency (Jiang et al., 2016), which may partly reflect the importance of Chinese agricultural imports from Africa.

By value chain the pattern of investments is slightly different by development partners than other groups, with relatively less emphasis on crops (∼40%, compared to >50% by governments and >90% by the private sector). About 15–20% of innovation funding by development partners ($300–400 million/year) went to livestock over the decade examined, and a similar amount to fisheries and aquaculture. However, between 2014 and 2018, bilateral and multilateral funders tripled their funding to fisheries and aquaculture, while philanthropies increased theirs tenfold. Finally, funding that cross-cuts all value chains constituted ∼12% of total funding by development partners.

One pattern worth further investigation is an apparent shift of innovation funding by development partners away from R&D during the decade, toward funding for uptake and scaling of innovations. Nearly 20% of innovation-related funds were spent on R&D for agriculture around 2010, which almost halved to under 10% by 2018. Examples of investment in scaling include funding by IDA in Tanzania's Accelerated Food Security Project, which included improving farmers' access to agricultural knowledge, technologies, marketing systems and infrastructure (World Bank,

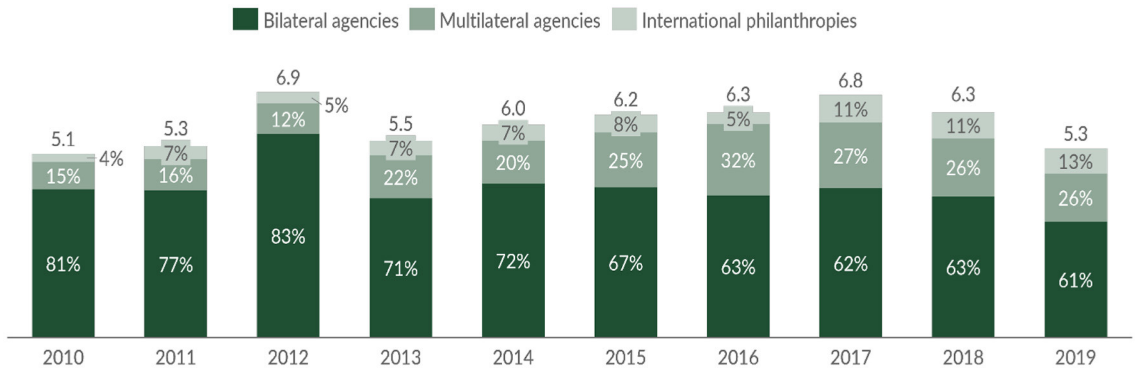


FIGURE 10
Funding by development partners in agricultural innovation focused on the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a) and OECD.Stat.

2014); and funding by the UK through an International Climate Fund with the intention to promote sustainable low-carbon land use and forest management in small and medium-scale farms by encouraging technological progress in Brazil (DEFRA, 2013). While uptake and scaling of current innovations is undoubtedly a very critical issue to address, particularly for small-scale farmers that are the majority producers in the Global South, investment in R&D is equally important for future transformation of food systems (Fuglie et al., 2019; Herrero et al., 2020), and it is important to maintain a good balance.

3.2. Innovation funding use by different systems

We segmented funding into three main systems (as shown in Figure 2). Layer 1, macro systems, includes governance and policy institutions, financing systems, knowledge and education systems within agriculture, as well as international and domestic trade. Layer 2, production systems, includes core agricultural value chains and production activity therein. Layer 3, ecosystem services and natural resource management systems, includes systems to manage, conserve or develop ecosystem services and underlying factors necessary for, or impacted by, agricultural production such as soil, water, biodiversity, forests and land.

The results in this section are a synthesis of all funder categories: governments (data here is mostly extrapolated from the Indian government due to data gaps—a major limitation), the private sector, PE/VC and development partners.

3.2.1. Macro systems (policy, financing, knowledge, trade systems)

During the period 2010–2019, an average of $20–25 billion was funded annually for innovations in macro systems, forming 30% of the overall agricultural innovation funding. For example, out of the USD 1.53B funding by the Indian government (mostly to ICAR), a large fraction (USD 0.96B) of innovation funding in this layer is focused on agricultural knowledge and education systems; staff costs and project related expenses at higher education institutes, universities and public research institutes. Other components of Layer 1—governance systems/policy support (USD 0.33B), financing (USD 0.23B) and collaboration and trade systems (USD < 0.01B)—received limited fractions of innovation funding. Such is also the case for CAAS in China, EMBRAPA in Brazil and KALRO in Kenya. Further, based on expert inputs, only a negligible portion of research projects in agricultural research institutes and education institutes gets commercialized. Therefore, more strategic integration of the private sector is needed that can not only improve commercialization but also improve private sector funding.

3.2.2. Agricultural production systems (across value chains)

About $25–35 billion (∼50% of the total) was funded annually for innovations in agricultural production systems, including production of inputs, processes, post-production, processing. Innovation funding into these areas comes from both governments (research funding, agricultural missions) and the private sector (research funding, production factories producing products and services, multi-disciplinary centers of innovation). Innovation projects in this area vary greatly; a few examples include the National Mission on Micro-Irrigation (Government of India, 2010) and Mission on Agriculture Mechanization (Government of India, 2017) and the Kenya Cereal Enhancement Programme (KALRO, n.d.). Funding in this category is also for demonstration projects at farms, to develop and distribute post-harvest technology, as well as research projects related to animal health.

Of the total innovation funds, the majority was for pre-harvest processing such as inputs (30%) and production (12%), while post-production (3%), processing (4%) and cross cutting (3%) received only little (Figure 11). Funding for farmer-saved and local seed systems was only about $2–6 million per year, or <0.5% of funding in innovation for seed systems for the Global South (Dalberg Asia, 2021e).

The private sector contributes ∼50% of the innovation funding in Layer 2, funding ∼$10–18 billion per year. Funding from large private corporations mostly goes to developing and marketing new

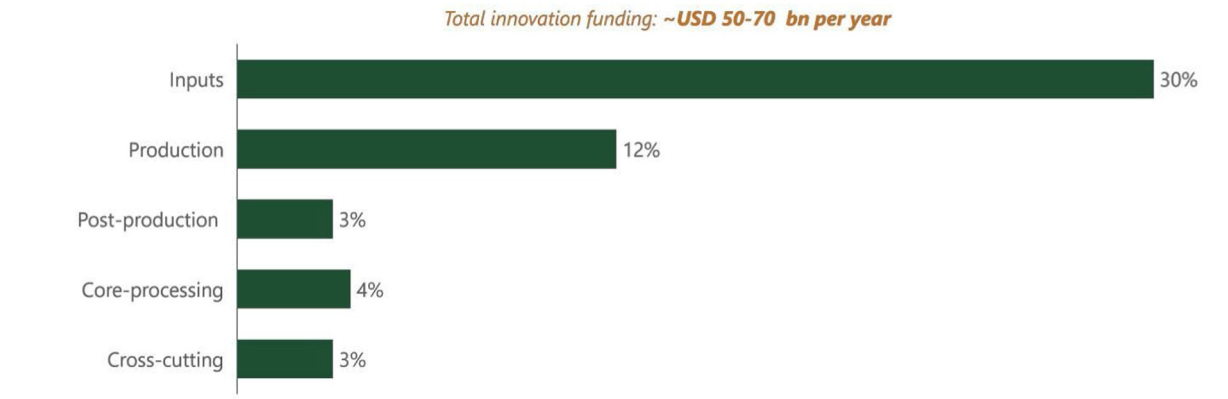


FIGURE 11
Percentage of total agricultural innovation funding by sub-layers in production systems 2010–2019 (annualized, constant 2019 prices). Source: Dalberg Asia (2021a).

production inputs. PE/VC funded startups tend to focus more on innovations in the post-production stage, covering supply chain technology as well as farmer engagement platforms, but are still small players.

3.2.3. Agriculture ecosystem services and natural resource management

Approximately $10 billion in innovation funding is utilized every year for the protection, conservation and development of ecosystem services as well as natural resource management; this represents ∼13–20% of all agricultural innovation funding. Funding toward these activities grew 5% annually over the decade examined, but still constituted the smallest portion across the three systems described above. Most of this innovation funding comes from government agencies or development partners, since this area is dominated by public goods that are not profitable for the private sector. This includes innovation in management of forests, biodiversity, soil and water conservation projects including watershed development, and training in new approaches in these areas. For example, IDA invests in countries in the Global South to improve water use efficiency through the adoption of water saving technologies and to increase surface and groundwater availability through the rehabilitation of small to medium irrigation schemes, terrace rehabilitation, bank protection works and other water and soil conservation activities (World Bank, 2016). Increasingly, however, there are startups that are focused on soil health management, water and biodiversity conservation through the use of data and analytics. For example, Shuxi Technology, a startup in China, provides data-driven precision agriculture solutions including recommendations to monitor soil health (Tracxn, n.d.a). An India-based startup, Sumo Agro, manufactures soil nutrients with the intention of supporting regenerative agriculture (Tracxn, n.d.b). The challenge for getting more private sector investment in innovation will be monetizing ecosystem benefits, which is proving challenging, although agricultural carbon payments are a growth area (IIF, 2021).

3.3. Funding innovation for sustainable agricultural intensification

We estimated that <$5 billion annually was targeted toward SAI innovation in the Global South, which is <7% of total funding over the period 2010–2019. Using our broad definition (where environment is the only "sustainability" element included), annual funding was around $3.4–4.7 billion, while using the narrow definition (which additionally requires a focus on social or human outcomes), the total was around $2–2.6 billion or <4.5% of total funding (Figure 12).

There is certainly much room for improvement in these estimates. Supplementary Figure 1 shows that all innovation intentions scored quite low; for example, intentions to improve productivity and economics were only mentioned for 28% of all funding, while other dimensions (environmental, social or human conditions) were much lower. Underestimates can result from poor descriptions of funding streams, in which specific intentions are not clearly indicated—although this is likely to be a more frequent problem with productivity (as some innovation proposal writers may assume productivity is an obvious objective and see no need to spell it out) than for environmental and social intentions. Scaling and extension activities may also lack clear descriptions of their intentions—particularly their environmental ones—which means that even in the case that they have clear socially-focused intentions, they would not get classified as SAI funding using our methods. Finally, as previously mentioned, an important limitation on the government estimates was that India was the only major country in the study sample that had sufficiently detailed data, so overall government estimates are based on the extrapolation of Indian numbers.

With the above caveats, it still seems reasonable to conclude that funding for innovation for SAI for the Global South is very low. Even tripling our figures would result in an estimate of a fifth or less of all funding with stated SAI intentions. Breaking down the numbers and data (with caution):

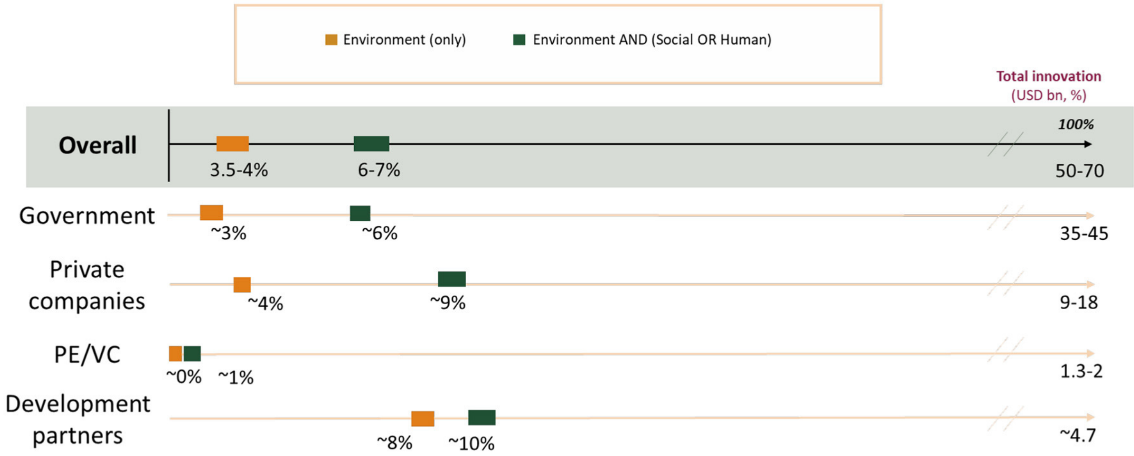


FIGURE 12
Funding for sustainable agricultural intensification as a share of innovation for narrow and broad definitions 2010–2019 (annualized, constant 2019 prices). Source: Dalberg Asia (2021a).

- The proportion of innovation funding that has stated intentions of SAI for the government (<6%) appears slightly less than for the private sector (∼9%) and development partners (∼10%). This might be mainly a matter of presentation and requires further investigation. The private sector, with valuable brands at stake, is being asked to focus more on environmental, social and governance (ESG) outcomes, so might be better than government entities at articulating sustainability goals. Many large-scale private sector companies have their own standards and metrics for sustainability (e.g., OLAM, n.d.; Bayer, 2022), although they may not always apply these consistently across all their innovation work. Similarly, most development partners have a strong strategic focus on sustainability and a requirement to clearly state their objectives in project and program descriptions. Bilateral and multilateral funding to SAI (excluding China) was estimated to increase by ∼10% annually between 2010 and 2018, but was still only ∼8–10% of the total innovation spend at the end of the period examined.
- From an agricultural value chain perspective, SAI innovation (using the broad definition) funding percentages are low, ranging from 8% for fisheries and aquaculture to 5% for crops and only 2% for livestock (Supplementary Figure 2). This suggests that the majority of funding emphasizes productivity enhancements and not the other dimensions of sustainability. An increased focus on overall sustainability by prominent private sector players in livestock—companies such as Tyson Foods (USA) and BRF (Brazil)—could drive up SAI funding for this sector, as many of these large players currently have limited stated intentions around environmental sustainability.
- From an innovation area perspective, ∼8% of funding for technology-related innovation has clear SAI intentions, in contrast to ∼4% of institutional innovation funding and ∼3% of marketing and extension innovation funding (Supplementary Figure 3). As mentioned, the latter figures may be underestimated, as if funding streams do not mention environmental intentions, they do not get tagged under either the broad or narrow definition of SAI.

4. Discussion

Improving food and nutrition security while meeting sustainability targets is one of the main global development challenges facing this generation. A rapid and fundamental shift to more productive, sustainable and equitable ways of producing food (here called sustainable agricultural intensification or SAI) is needed, requiring significant innovation across different categories: technology, business practices, social institutions, finance, and policies (Tomich et al., 2019; Barrett et al., 2020; Blended Finance Taskforce, 2020; Fanzo et al., 2020; Herrero et al., 2020; Steensland, 2021).

This study estimates that overall innovation funding for the agrifood sector for the Global South (which in this study includes both R&D funding and the extension, marketing and other funding for innovation uptake) is around $60 billion ($50–70 billion) per year in 2019 US dollars, or around 4.5% of sector output. For such a critical sector, this seems relatively low: as a comparator, if funding were raised to match levels found in the renewable energy sector (Osborne, 2019), this would imply an additional $20 billion per year in funding. Rosegrant et al. (2022), in this collection, have estimated the size of the "investment gap" for research and innovation to meet some key Sustainable Development Goals (principally calorie-based hunger and greenhouse gas emissions) and project that this would need a minimum of $10.5 billion additional funding annually. Baldos et al. (2020) have also pointed out the significant global investment needed for agriculture to adapt to climate change.

We estimated that on average, across funder types, about 20% of innovation funding was allocated to R&D—with the largest share allocated to extension, marketing and behavior change (∼33%) and the rest to institutions, education and infrastructure. For development partners, there was a significant move away from R&D funding over the period examined (from nearly 20% of funding in 2010 to about 10% by 2019), with increased funding going to supporting scaling up existing innovations. Innovation uptake and user-led innovation are clearly areas needing support (MacMillan and Benton, 2014; Fuglie et al., 2019). However, it is also worth keeping an eye on the balance between these medium-term needs and the long-term, risky, but critical R&D funding needed to develop and pilot new institutions, practices, varieties, technologies and bundles thereof (Barrett et al., 2020) to address emerging issues.

An important finding is that only a small fraction of innovation funding within the agricultural sector has intentions of SAI, and that this fraction has not increased substantially in recent years. We estimate that over the decade examined (2010–2019), <$5–7 billion out of this (<7%) had visible environmental intentions, and <5% had both environmental and social/human intentions. Even allowing for challenges with these estimates, it appears that funding for SAI innovation is far too low to support transformation of food systems.

Finally, this study has revealed a widespread lack of availability, granularity and quality of the data on investment in innovation across all funder types, as well as a lack of common definitions, in particular for what funding is counted as promoting sustainability. This is a major cause for concern, as it is not possible to improve investment without adequate information.

What can be done to improve this situation? Five potential recommendations are suggested by this study.

First, all funder types need to increase their funding on research and innovation for agrifood systems, particularly for the Global South, which faces the most significant challenges of poverty, food insecurity and the effects of climate change.

Second, a global tracking system for research and innovation in agrifood systems is urgently needed, both to incentivize funders and innovators and to spot key gaps in investment. While there are several programs which currently track agrifood R&D and innovation, global coverage is patchy, financing is not always reliable, and systems are not harmonized. Based on the emerging findings of the working paper on which this report is based (Dalberg Asia, 2021a), CoSAI actively campaigned with others for the establishment of a global tracking system that would also include sustainability concerns (CoSAI, 2021; Compton et al., 2022). The United Nations Food and Agriculture Organization (FAO) has an important convening role. Its recently released report (FAO, 2022) introduces the vision, rationale, scope and methods for new Agrifood Systems Technologies and Innovation Outlook (ATIO), which will curate and publish information on innovation inputs and emerging and mature innovations as well as their potential to transform the agrifood system.

Third, a clear common framework and standards for measurement would be required to support a tracking system. This would need to cover general issues such as how to tag different types of innovation (e.g., in policy or finance), stages of research and innovation, and specific topics such as crops, as well as the degree of detail to collect (e.g., crops-cereals-maize-popcorn-popcorn variety x). FAO (2022) discusses this in detail, and also emphasizes the need for indicators and open access data for decision making and investment planning.

Fourth, as part of this, an agreed framework is needed to be able to distinguish more clearly what "counts" as funding for sustainability. While many investors and companies have started indicating their interest in supporting environmentally and socially sustainable agriculture, this has not translated into significant changes, in part because of ambiguous definitions and non-standard metrics. A common framework and measurement scale should be created by international institutions and used by funders. This should be based in the first instance on stated intentions [as in this study and other studies tracking innovation funding, such as Biovision and IPES Food (2020)], because the importance of clearly-stated desired outcomes is acknowledged in all planning for applied research and innovation (Andrew and Hildebrand, 2019). However, it is also important to have a means to track that stated intentions are in fact leading toward desired sustainability outcomes. There are successful examples of sustainability indicators used for some agricultural research, for example the Sustainability Intensification Assessment Framework by Musumba et al. (2017) and Stewart et al. (2018), used by projects funded by the US Agency for International Development (USAID). However, it is very challenging to come up with universally-applicable indicators for all types of agrifood innovation, due to the context-specificity, high drop-out rates and long time scales from innovation to impact at scale—and the complexity and high cost of attributing observed outcomes to specific innovations (Stevenson et al., 2018; Belcher and Hughes, 2021). Another article in this Research Topic (forthcoming, based on the working paper Zurek et al., 2022) tries to resolve this dilemma by proposing common principles for innovation that include verifying that the project/program is measuring progress toward agreed areas (food security, social equity, etc.) using suitable metrics for the context (Zurek et al., 2023). However, there are still many issues to resolve, including the perceived degree of sustainability (e.g., Biovision and IPES Food, 2020), and the balance between having many sustainability objectives and one or two highly focused ones that can be more rigorously measured and enforced (Tricks, 2022). The recent report from FAO (2022) also emphasizes the need for systematic tracking of data and filling the gaps.

Fifth, governance regimes and independent watchdog bodies need to include research and innovation in their oversight of agrifood investment. For example, the World Benchmarking Alliance and the Global Impact Investors Network both have influential agrifood monitoring systems (GIIN, 2020; World Bench Marking Alliance, 2022) but neither currently include indicators for research and innovation, although this is critical for future performance and sustainability.

The above five recommendations have implications for all funders. For example:

Governments of Global South countries can benefit from increasing their investment in research and innovation in agrifood systems (Alston et al., 2021; Stads et al., 2021). This can potentially be done by repurposing some existing funding, e.g., for some types of agrifood subsidies (FAO et al., 2021; OECD, 2021; Springmann and Freund, 2022). Governments could also aim to improve their tracking of funding for innovation, including common databases across ministries and departments, and move to adopt international standards for sustainability.

Private sector companies, in particular the enormous transnational corporations that dominate global technical R&D in global agrifood systems, have immense potential to promote or hinder sustainability (Folke et al., 2019; Schneider et al., 2020). Focusing all (or a larger part) of their research and innovation on sustainability could potentially have a huge effect.

Development partners have the funds, the networks and the influence to create a standard within the development sector for measuring SAI-related innovation funding. They could be the first movers, proving the benefits of measuring funding on a common sustainability standard and then advocating for its use across all types of funders including Global South governments, other international agencies, and private investors as well as their own funding.

This is a challenging agenda. *Civil society organizations and watchdogs* can play a role in pushing the major funders, but agrifood innovation has not traditionally been high on their list of demands. Strong social norms and governance regimes will be important in motivating change in innovation goals and objectives (Béné, 2022).

We acknowledge the importance of gender, division of labor, and producer sub-groups based on landholdings. However, we were not able to disaggregate data under those categories due to lack of granularity in the available data. It important that biophysical and social innovations are equitable and available to all categories and does not discriminate against any particular group including subsistence and commercial sectors. In addition, we could not separate data on farmers uptake of funding and innovations, but recognize that these are important challenges and reasons for low adoption and impact, especially in some regions of sub-Saharan Africa. There is certainly a need for balancing funds toward new innovations and adoption or scaling to reduce poverty and hunger, and improve food, nutrition and climate security.

This study was not designed to identify specific areas of under-funding—some of these have already been highlighted by other authors (e.g., Pingali, 2015; Haddad et al., 2016; Beintema and Stads, 2019; Tadele, 2019; Bollington et al., 2021). The decision on how much innovation funding should be allocated to a particular area is complex and often situation-specific. Nevertheless, a couple of areas stood out in this study as having potentially very low funding:

- Funding for innovation for post-harvest management and value chains in the Global South was estimated at less than a tenth of innovation in production and production inputs. This is potentially a major global area of under-investment, since post-production innovation plays a huge part in developing value chains (Reardon et al., 2019) and also in reducing food waste, which *inter alia* has important food security and climate change mitigation impacts (Chen et al., 2020; Cattaneo et al., 2021; Santeramo and Lamonaca, 2021).
- Another area of apparent underinvestment is farmer-produced and local seed systems. Innovation in local informal seed systems and farmer-saved seed gets <0.5% of all seed innovation funding, although these are the most important source of seeds for many farmers in the Global South (Coomes et al., 2015; McGuire and Sperling, 2016).

5. Conclusion

This study represents, to the best of our knowledge, the first attempt to measure funding going toward agricultural innovation in the Global South by governments, the private sector, development partners and PE/VC investors—going beyond technical R&D to measure complementary funding in scale-up and adoption as well as funding in innovation in policies, financial instruments and social institutions. In addition, this represents the first global attempt to measure the proportion of this funding to SAI that has stated intentions of promoting environmental, social or human sustainability.

Among the more striking patterns, we found that funding to innovation represents only 4.5% of Global South agricultural output, and that <7% of this agricultural innovation funding is explicitly focused on delivering environmental outcomes, while <5% has both environmental and social/human intentions. Specific areas which received very low innovation funding included post-production systems and local seed systems.

The results of this study were limited by the availability and quality of data on innovation. An important recommendation is the need to direct more funding toward creating a standardized approach to cataloging, classifying and measuring funding in innovation in agriculture being made by different categories of funders globally. Such a common standard of reporting agricultural innovation funding would go a long way in making future analysis easier and increased transparency about sustainability intentions would increase incentives for change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PVVP, NBh, JC, and RE conceived the approach to the research and led all aspects. NBh, VB, GJ, and KN conducted the analysis. All authors contributed to writing and editing and approved the final manuscript.

Funding

This research communicated as part of this paper was commissioned and funded by the Commission on Sustainable Agriculture Intensification (CoSAI). CoSAI was initiated and supported by the CGIAR Research Program on Water, Land, and Ecosystems (WLE), funded by the CGIAR Trust Fund and other donors (https://cgiar.org/funders). CoSAI Commissioners are independent, and facilitated by a Secretariat based at the

International Water Management Institute (IWMI) headquarters in Colombo, Sri Lanka. Partial funding support from Feed the Future Sustainable Intensification Innovation Lab funded by United States Agency for International Development (Cooperative Agreement # AID-OAA-L-14-00006). Contribution number 23-117-J from Kansas Agricultural Experiment Station.

Acknowledgments

This article is based on working paper (Dalberg Asia, 2021a) and associated methodology (Dalberg Asia, 2021b) from a study conducted by Dalberg Advisors (India) on behalf of the Commission on Sustainable Agriculture Intensification (CoSAI) and hosted on the CoSAI: https://www.iwmi.cgiar.org/archive/cosai/ and at https://hdl.handle.net/10568/114762. Acknowledgments for the full team, oversight group and others involved in the original study are included in the working paper.

Conflict of interest

NBh, VB, GJ, and KN were employed by Dalberg Advisors. PF was employed by Scriptoria.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer DS declared a past collaboration with the authors PVVP, NBh, RE, NBe, and JC to the handling editor.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1108949/full#supplementary-material

References

Alston, J. M., Pardey, P. G., and Rao, X. (2021). *Rekindling the Slow Magic of Agricultural RandD. Issues in Science and Technology, May 3*. Available online at: https://issues.org/rekindling-magic-agricultural-research-development-alston-pardey-rao (accessed November 21, 2022).

Andrew, C. O., and Hildebrand, P. E. (2019). *Planning And Conducting Applied Agricultural Research*. Boca Raton, FL: CRC Press.

Baldos, U. L. C., Fuglie, K. O., and Hertel, T. W. (2020). The research cost of adapting agriculture to climate change: A global analysis to 2050. *Agricult. Econ.* 51, 207–220. doi: 10.1111/agec.12550

Barrett, C. B., Benton, T. G., Cooper, K. A., Fanzo, J., Gandhi, R., Herrero, M., et al. (2020). Bundling innovations to transform agri-food systems. *Nat. Sustain.* 3, 974–976. doi: 10.1038/s41893-020-00661-8

Bayer (2022). *Product Stewardship: Commitment, Principles and Key Requirements*. Monheim, Germany: Bayer. Available online at: https://bayer.com/en/agriculture/product-stewardship (accessed November 15, 2022).

Beintema, N., Nin Pratt, A., and Stads, G.-J. (2020). *ASTI Global Update 2020*. Washington, DC: International Food Policy Research Institute. Available online at: https://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/134029/filename/134242.pdf (accessed November 15, 2022).

Beintema, N. M., and Stads, G.-J. (2019). Measuring agricultural research investments: a revised global picture. *Gates Open Res.* 3, 459. doi: 10.21955/gatesopenres.1115643.1

Belcher, B. M., and Hughes, K. (2021). Understanding and evaluating the impact of integrated problem-oriented research programmes: concepts and considerations. *Res. Eval.* 30, 154–168. doi: 10.1093/reseval/rvaa024

Béné, C. (2022). Why the Great Food Transformation may not happen—a deep-dive into our food systems' political economy, controversies and politics of evidence. *World Develop.* 154, 105881. doi: 10.1016/j.worlddev.2022.105881

Biovision and IPES Food (2020). *Money Flows: What is Holding Back Investment in Agroecological Research for Africa? Biovision Foundation for Ecological Development and International Panel of Experts on Sustainable Food Systems*. Available online at: https://www.agroecology-pool.org/moneyflowsreport (accessed November 15, 2022).

Blended Finance Taskforce (2020). *Better Finance, Better Food: Investing in the New Food and Land Use Economy*. London: Blended Finance Taskforce. Available online at: https://www.blendedfinance.earth/s/Better-Finance-Better-Food-Investing-in-the-new-food-and-land-use-economy-pc86.pdf (accessed November 15, 2022).

BMGF (2020). *Committed Grants*. Seattle: Bill and Melinda Gates Foundation. Available online at: https://www.gatesfoundation.org/about/committed-grants (accessed October 22, 2022).

Bollington, A., DeLonge, M., Mungra, D., Hayek, M., Saifuddin, M., and McDermid, S. S. (2021). Closing research investment gaps for a global food transformation. *Front. Sustain. Food Syst.* 5, 454. doi: 10.3389/fsufs.2021.794594

Cattaneo, A., Sánchez, M. V., Torero, M., and Vos, R. (2021). Reducing food loss and waste: five challenges for policy and research. *Food Policy* 98, 101974. doi: 10.1016/j.foodpol.2020.101974

Chai, Y., Pardey, P. G., Chan-Kang, C., Huang, J., Lee, K., and Dong, W. (2019). Passing the food and agricultural RandD buck? the United States and China. *Food Policy* 86, 101729. doi: 10.1016/j.foodpol.2019.101729

Chaudhury, D. R. (2020). *With Rising Population and Declining Arable Land, China may be Staring at a Major Food Crisis. The Economic Times*. Available online at: https://economictimes.indiatimes.com/news/international/world-news/with-rising-population-and-declining-arable-land-china-may-be-staring-at-a-major-food-crisis/articleshow/77942570.cms (accessed October 19, 2022).

Chen, C., Chaudhary, A., and Mathys, A. (2020). Nutritional and environmental losses embedded in global food waste. *Resour. Conserv. Recycl.* 160, 104912. doi: 10.1016/j.resconrec.2020.104912

Cirera, X., and Maloney, W. F. (2017). *The Innovation Paradox: Developing-Country Capabilities and the Unrealized Promise of Technological Catch-Up*. Washington, DC: The World Bank. Available online at: https://openknowledge.worldbank.org/bitstream/handle/10986/28341/9781464811609.pdf (accessed November 15, 2022).

Compton, J., Stads, G.-J., Barrett, C. B., Herrero, M., Arndt, C., Prasad, P. V. V., et al. (2022). *Global Tracking of Agrifood Research and Innovation for Meeting Food Security and Sustainable Development Goals. Jakarta, Indonesia: T20*. Available online at: https://www.global-solutions-initiative.org/policy_brief/global-tracking-of-agrifood-research-and-innovation-for-meeting-food-security-and-sustainable-development-goals (accessed November 15, 2022).

Coomes, O. T., McGuire, S. J., Garine, E., Caillon, S., McKey, D., Demeulenaere, E., et al. (2015). Farmer seed networks make a limited contribution to agriculture? *Four* common misconceptions. *Food Policy* 56, 41–50. doi: 10.1016/j.foodpol.2015.07.008

CoSAI (2021). *Reorienting Funding for Research and Innovation is an Urgent Step to Transform Agri-food Systems. CoSAI Policy Brief #1*. Colombo, Sri Lanka: Commission for Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/119839 (accessed November 15, 2022).

Dalberg Asia (2021a). *Funding Agricultural Innovation for the Global South: Does it Promote Sustainable Agricultural Intensification*? Colombo,: Commission on Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/114762 (accessed November 15, 2022).

Dalberg Asia (2021b). *Funding Agricultural Innovation for the Global South: Does it Promote Sustainable Agricultural Intensification? Methodology Report*. Colombo: Commission on Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/115259 (accessed November 15, 2022).

Dalberg Asia (2021c). *Case Study: Brazil's Investment in Innovation for Sustainable Agricultural Intensification*. Colombo: Commission on Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/115046 (accessed November 15, 2022).

Dalberg Asia (2021d). *Case Study: Finance for Sustainable Agricultural Intensification*. Colombo: Commission on Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/115045 (accessed November 15, 2022).

Dalberg Asia (2021e). *Case Study: Investment in Sustainable Seeds for Sustainable Agricultural Intensification*. Colombo: Commission on Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/115261 (accessed November 15, 2022).

DEFRA (2013). *Department for Environment, Food and Rural Affairs: Intervention Summary: Low Carbon Agriculture for Avoided Deforestation and Poverty Reduction in Brazil. Department for Environment, Food and Rural Affairs, August 2013, PB14023*. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/229597/pb14023-low-carbon-agri-intervention-summary.pdf (accessed November 15, 2022).

Dehmer, S. P., Pardey, P. G., Beddow, J. M., and Chai, Y. (2019). Reshuffling the global RandD deck, 1980-2050. *PLOS One* 14, e0213801. doi: 10.1371/journal.pone.0213801

Dion, M., Ho, S., Figueiras, S., and Perez, A. (2020). The *Asia Alternative Protein Industry Report 2020*. Hong Kong: Green Queen Media. Available online at: https://www.greenqueen.com.hk/wp-content/uploads/2020/02/The-Asia-Alternative-Protein-Industry-Report-2020-New-Decade-New-Protein.pdf (accessed November 15, 2022).

FAIRR (2021). *Building ESG into the Alternative Protein Terrain*. London: The FAIRR Initiative. Available online at: https://www.fairr.org/sustainable-proteins/food-tech-spotlight/building-esg-into-food-tech (accessed October 19, 2022).

Fanzo, J., Covic, N., Dobermann, A., Henson, S., Herrero, M., Pingali, P., et al. (2020). A research vision for food systems in the 2020s: defying the status quo. *Global Food Secur.* 26, 100397. doi: 10.1016/j.gfs.2020.100397

FAO (2022). *Introducing the Agrifood Systems Technologies and Innovations Outlook (ATIO)*. Rome: Food and Agriculture Organization. Available online at: https://www.fao.org/3/cc2506en/cc2506en.pdf (accessed November 15, 2022).

FAO, UNDP, and UNEP (2021). A multi-billion-dollar opportunity—repurposing agricultural support to transform food systems: in "Brief," Rome, Italy: Food and Agriculture Organization, United Nations Development Programme and United Nations Environment Programme. Available online at: http://www.fao.org/documents/card/en/c/CB6683EN (accessed November 15, 2022).

Folke, C., Österblom, H., Jouffray, J.-B., Lambin, E. F., and Adger, W. N., Scheffer, M., et al. (2019). Transnational corporations and the challenge of biosphere stewardship. *Nat. Ecol. Evol.* 3, 1396–1403. doi: 10.1038/s41559-019-0978-z

Frontier Economics (2014). *Rates of Return to Investment in Science and Annovation: A Report Prepared for the UK Department for Business, Innovation and Skills (BIS)*. London, UK: Frontier Economics. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/333006/bis-14-990-rates-of-return-to-investment-in-science-and-innovation-revised-final-report.pdf (accessed November 15, 2022).

Fuglie, K. (2016). The growing role of the private sector in agricultural research and development world-wide. *Global Food Secur.* 10, 29–38. doi: 10.1016/j.gfs.2016.07.005

Fuglie, K., Gautam, M., Goyal, A., and Maloney, W. F. (2019). *Harvesting Prosperity: Technology and Productivity Growth in Agriculture*. Washington, DC: The World Bank. Available online at: http://documents1.worldbank.org/curated/ar/845031568696802783/pdf/Harvesting-Prosperity-Technology-and-Productivity-Growth-in-Agriculture.pdf (accessed November 15, 2022).

Fuglie, K., Wiebe, K., Sulser, T. B., Cenacchi, N., and Wilenbocket, D. (2022). Multidimensional impacts from international agricultural research: implications for research priorities authors and affiliations. *Front. Food Syst.* 22, 562. doi: 10.3389/fsufs.2022.1031562

Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., et al. (2013). Sustainable intensification in agriculture: premises and policies. *Science* 341, 33–34. doi: 10.1126/science.1234485

Gatti, L., Seele, P., and Rademacher, L. (2019). Grey zone in—greenwash out: a review of greenwashing research and implications for the voluntary-mandatory transition of CSR. *Int. J. Corpor. Soc. Responsibil.* 4, 6. doi: 10.1186/s40991-019-0044-9

GIIN (2020). *Understanding Impact Performance: Agriculture Investments*. New York, NY: Global Impact Investing Network. Available online at: https://thegiin.org/assets/Understanding%20Impact%20Performance_Agriculture%20Investments_webfile.pdf (accessed November 15, 2022).

GINSEP (2021). *Plantix: How an AgriTech startup is helping Indian farmers fight crop diseases. GINSEP News Blog*. Available online at: https://ginsep.co/plantix-how-an-agritech-start-up-is-helping-indian-farmers-fight-crop-diseases (accessed October 19, 2022).

Gliessman, S. R. (2015). *Agroecology: The Ecology of Sustainable Food Systems, Third Edition*. Boca Raton, FL: Taylor and Francis.

Government of India (2010). *National Mission on Micro Irrigation—Operational Guidelines*. Available online at: https://www.nccd.gov.in/PDF/Guidelines-NMMI.pdf (accessed November 15, 2022).

Government of India (2017). *Sub-Mission on Agricultural Mechanization—Operational Guidelines*. Available online at: https://agrimachinery.nic.in/Files/Guidelines/smam.pdf (accessed November 15, 2022).

Haddad, L., Hawkes, C., Webb, P., Thomas, S., Beddington, J., Waage, J., et al. (2016). A new global research agenda for food. *Nature* 540, 30–32. doi: 10.1038/540030a

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Benton, T. G., Bodirsky, B. L., et al. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nature Food* 1, 266–272. doi: 10.1038/s43016-020-0074-1

Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., et al. (2015). Livestock and the environment: What have we learned in the past decade? *Annual Rev. Environ. Resour.* 40, 177–202. doi: 10.1146/annurev-environ-031113-093503

IIF (2021). *Taskforce on Scaling Voluntary Carbon Markets Final Report*. Washington, DC: Institute of International Finance. Available online at: https://iif.com/Portals/1/Files/TSVCM_Report.pdf (accessed November 15, 2022).

Jiang, L., Harding, A., Anseeuw, W., and Alden, C. (2016). Chinese agriculture technology demonstration centres in Southern Africa: the new business of development. *The Public Sphere* 2016, 7–36. Available online at: https://agritrop.cirad.fr/582983/1/ATDC%20Paper.pdf (accessed November 15, 2022).

KALRO (n.d.). *Kenya Cereal Enhancement Programme—Climate Resilient Agricultural Livelihood Window (KCEP-CRAL)*. Nairobi, Kenya: Kenya Agricultural and Livestock Research Organization. https://www.kalro.org/research-projects/kenya-cereal-enhancement-programme-climate-resilient-agricultural-livelihood-window-kcep-cral (accessed October 19, 2022).

Kurth, T., Möller, C., Jerratsch, J.-F., Adolphs, B., Wübbels, G., and Walker, D. (2020). *Reviving Agricultural Innovation in Seeds and crop Protection. BCG*. Available online at: https://www.bcg.com/publications/2020/reviving-agricultural-innovation-seeds-crop-protection (accessed November 15, 2022).

MacMillan, T., and Benton, T. (2014). Agriculture: engage farmers in research. *Nature* 509, 25–27. doi: 10.1038/509025a

Maredia, M. K., Shankar, B., Kelley, T. G., and Stevenson, J. R. (2014). Impact assessment of agricultural research, institutional innovation, and technology adoption: introduction to the special section. *Food Policy* 44, 214–217. doi: 10.1016/j.foodpol.2013.10.001

McGuire, S., and Sperling, L. (2016). Seed systems smallholder farmers use. *Food Security*. 8, 179–195. doi: 10.1007/s12571-015-0528-8

Mockshell, J., and Kamanda, J. (2018). Beyond the agroecological and sustainable agricultural intensification debate: Is blended sustainability the way forward? *Int. J. Agricult. Sustain.* 16, 127–149. doi: 10.1080/14735903.2018.1448047

Musumba, M., Grabowski, P., Palm, C., and Sieglinde, S. (2017). *Guide for the Sustainable Intensification Assessment Framework*. Manhattan, KS: USAID and Kansas State University. Available online at: https://www.k-state.edu/siil/documents/docs_siframework/Guide%20for%20SI%20Assessment%20Framework%20-%2010.24.17.pdf (accessed November 15, 2022).

Njuki, J., and Nicol, A. (2021). *National Policies and Strategies for Food, Land and Water Systems Transformation (NPS): Proposal, September 28, 2021*. Montpellier, France: CGIAR Available online at: https://storage.googleapis.com/cgiarorg/2021/10/INIT27-National-Policies-and-Strategies-for-Food-Land-and-Water-Systems-Transformation_Final_07.10.2021.pdf (accessed November 15, 2022).

OECD (2019). *Innovation, Productivity and Sustainability in Food and Agriculture: Main Findings from Country Reviews and Policy Lessons*. Paris: Organisation for Economic Co-operation and Development.

OECD (2021). *Agricultural Policy Monitoring and Evaluation 2021: Addressing the Challenges Facing Food Systems*. Paris: Organisation for Economic Co-operation and Development.

OLAM (n.d.). *Methodology: Our Metrics. OLAM AtSource*. Available online at: https://atsource.io/methodology.html (accessed October 19, 2022).

Osborne, M. (2019). *RandD spending analysis of 21 PV Manufacturers*. Available online at: https://www.pv-tech.org/rd-spending-analysis-of-21-pv-manufacturers/ (accessed November 15, 2022).

Pingali, P. (2015). Agricultural policy and nutrition outcomes—getting beyond the preoccupation with staple grains. *Food Secur.* 7, 583–591. doi: 10.1007/s12571-015-0461-x

Pray, C. E., and Fuglie, K. O. (2015). Agricultural research by the private sector. *Ann. Rev. Resour. Econ.* 7, 399–424. doi: 10.1146/annurev-resource-100814-125115

Pretty, J. N. (1997). The sustainable intensification of agriculture: making the most of the land. *Nat. Resour. Forum* 21, 247–256 doi: 10.1111/j.1477-8947.1997.tb00699.x

Reardon, T., Echeverria, R., Berdegué, J., Minten, B., Liverpool-Tasie, S., Tschirley, D., et al. (2019). Rapid transformation of food systems in developing regions: Highlighting the role of agricultural research and innovations. *Agricult. Syst.* 172, 47–59. doi: 10.1016/j.agsy.2018.01.022

Rijsberman, F. (2016). *Getting the research response to hunger right: Is it our last shot? Huffington Post*. Available online at: https://huffpost.com/entry/getting-the-research-resp_b_9640894 (accessed October 6, 2022).

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., et al. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* 46, 4–17. doi: 10.1007/s13280-016-0793-6

Rosegrant, M. W., Sulser, T. B., and Wiebe, K. (2022). Global investment gap in agricultural research and innovation to meet sustainable development goals for hunger and paris agreement climate change mitigation. *Front. Sustain. Food Syst.* 6, 67. doi: 10.3389/fsufs.2022.965767

Santeramo, F. G., and Lamonaca, E. (2021). Food loss–food waste–food security: a new research agenda. *Sustainability* 13, 4642. doi: 10.3390/su13094642

Schneider, A., Hinton, J., Collste, D., González, T. S., Cortes-Calderon, S. V., and Aguiar, A. P. D. (2020). Can transnational corporations leverage systemic change towards a 'sustainable' future? *Nat. Ecol. Evol.* 4, 491–492. doi: 10.1038/s41559-020-1143-4

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., Matthews, E., et al. (2019). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050. Final Report*. Washington, DC: World Resources Institute. Available online at: https://research.wri.org/wrr-food (accessed November 15, 2022).

Springmann, M., and Freund, F. (2022). Options for reforming agricultural subsidies from health, climate, and economic perspectives. *Nat. Commun.* 13, 82. doi: 10.1038/s41467-021-27645-2

Stads, G., Nin-Pratt, A., and Beintema, N. (2021). *Building a Case for Increased Investment in Agricultural Research in Africa. Report Commissioned by AU-SAFGRAD. Ouagadougou*, Burkina Faso: African Union. Available online at: https://asti.cgiar.org/ag-rnd-africa (accessed November 15, 2022).

Steensland, A. (2021). *2021 Global Agricultural Productivity Report: Climate for Sustainable Agricultural Growth*. Blacksburg, VA, USA: Virginia Tech College of Agriculture and Life Sciences. Available online at: https://globalagriculturalproductivity.org/wp-content/uploads/2021/10/2021-GAP-Report.pdf (accessed November 15, 2022).

Stevenson, J., Macours, K., and Gollin, D. (2018). The rigor revolution in impact assessment: implications for CGIAR. Rome, Italy: CGIAR Independent Science and Partnership Council. Available online at: https://cas.cgiar.org/sites/default/files/pdf/ispc_synthesis_study_rigor_revolution_cgiar.pdf (accessed November 15, 2022).

Stewart, Z. P., Middendorf, B. J., Musumba, M., Grabowski, P., Palm, C., Snapp, S., et al. (2018). Sitoolkit.com. *Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification, Kansas State University, Manhattan, Kansas, USA*.

Tadele, Z. (2019). Orphan crops: their importance and the urgency of improvement. *Planta* 250, 677–694. doi: 10.1007/s00425-019-03210-6

Tomich, T. P., Lidder, P., Coley, M., Gollin, D., Meinzen-Dick, R., Webb, P., et al. (2019). Food and agricultural innovation pathways for prosperity. *Agricult. Syst.* 172, 1–15. doi: 10.1016/j.agsy.2018.01.002

Tracxn (n.d.a). *Shuxi Technology—Company Profile. Tracxn*. Available online at: https://tracxn.com/d/companies/shuxitech.com (accessed November 15, 2022).

Tracxn (n.d.b). *Sumo Agro—Company Profile. Tracxn*. Available online at: https://tracxn.com/d/companies/sumaagro.com

Tricks, H. (2022). "ESG investing: A broken system needs urgent repairs," in *ESG Investing: Special Report from The Economist*. London, UK: The Economist. Available online at: https://economist.com/special-report/2022-07-23 (accessed November 15, 2022).

United Nations (2022). *World Population Prospects*. New York, NY: United Nations Department of Economic and Social Affairs Statistics Division. Available online at: https://unstats.un.org/unsd/methodology/m49 (accessed October 19, 2022).

Waters-Bayer, A., Kristjanson, P., Wettasinha, C., van Veldhuizen, L., Quiroga, G., Swaans, K., et al. (2015). Exploring the impact of farmer-led research supported by civil society organisations. *Agricult. Food Secur.* 4, 1–7. doi: 10.1186/s40066-015-0023-7

World Bank (2014). *Tanzania—Accelerated Food Security Project (English)*. Washington, DC: The World Bank. http://documents.worldbank.org/curated/en/132691468106739354/Tanzania-Accelerated-Food-Security-Project (accessed October 19, 2022).

World Bank (2016). *Water, Water (Not) Everywhere: the Imperative of Increasing Water Use Efficiency. Blog*. Available online at: https://www.worldbank.org/en/news/feature/2016/08/18/the-imperative-of-increasing-water-use-efficiency (accessed November 22, 2022).

World Bank (2022). *World Water Day 2022: How India is Addressing It Water Needs*. Washington, DC: The World Bank. Available online at: https://www.worldbank.org/en/country/india/brief/world-water-day-2022-how-india-is-addressing-its-water-needs (accessed October 19, 2022).

World Bench Marking Alliance. (2022). *Methodology for the 2023 Food and Agriculture Benchmark*. World Bench Marking Alliance. Available online at: https://assets.worldbenchmarkingalliance.org/app/uploads/2022/12/WBA-2023-Food-and-Agriculture-Benchmark-methodology.pdf (accessed November 15, 2022).

Zurek, M., Hebinck, A., Wirths, J., Al-Malalha, M., and Crawford, S. (2022). *Task Force on Principles and Metrics for Innovation in Sustainable Agri-food Systems: Final Report*. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. Available online at: https://hdl.handle.net/10568/119439 (accessed November 15, 2022).

Zurek, M., Wirths, J., Hebinck, A., Crawford, S., Lidder, P., Prasad, P. V. V., et al. (2023). Principles for research and innovation in agrifood systems. *Front. Food Syst.* 22, 11. (in press).

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 01 August 2023
DOI 10.3389/fsufs.2023.1129419

OPEN ACCESS

EDITED BY
Julia Compton,
Independent Researcher, Cardiff,
United Kingdom

REVIEWED BY
Munyaradzi Junia Mutenje,
International Maize and Wheat Improvement Centre (CIMMYT), Zimbabwe
Stanley Karanja Ng'ang'a,
International Center for Tropical Agriculture (CIAT), Colombia
Ruben G. Echeverria,
Bill and Melinda Gates Foundation,
United States

*CORRESPONDENCE
Anne G. Timu
✉ A.timu@cgiar.org

RECEIVED 21 December 2022
ACCEPTED 29 June 2023
PUBLISHED 01 August 2023

CITATION
Kramer B, Timu AG and Damba O (2023) Estimating the intrahousehold costs and benefits of innovations to enhance smallholder farmers' resilience.
Front. Sustain. Food Syst. 7:1129419.
doi: 10.3389/fsufs.2023.1129419

Estimating the intrahousehold costs and benefits of innovations to enhance smallholder farmers' resilience

Berber Kramer[1], Anne G. Timu[2]* and Osman Damba[3]

[1]Markets, Trade and Institutions Unit, International Food Policy Research Institute (IFPRI), Nairobi, Kenya, [2]International Food Policy Research Institute, Washington, DC, United States, [3]Department of Agricultural and Food Economics, University for Development Studies (UDS), Tamale, Ghana

This paper introduces a new framework to quantify costs and benefits for resilience-related outcomes of agricultural innovations targeting smallholder farmers. The framework employs a non-unitary household model with expected utility to quantify welfare benefits associated with non-monetary outcomes that are important from a development perspective, such as improved consumption smoothing, empowerment, and changes in time use. We demonstrate the application of the framework using a case study of climate information services (CIS) in Ghana. We develop a set of individual bargaining weights based on the women's empowerment in agriculture index, to demonstrate how benefits from CIS are distributed among men and women within households. We find that for the average risk-averse farmer, using CIS is associated with a 37-percent increase in expected utility, but male household heads benefit more than women living in male-headed households. Cost–benefit analyses that do not consider the intrahousehold distribution of benefits associated with agricultural innovations will overestimate benefits accruing to women with low bargaining power.

KEYWORDS

cost-benefit analysis, climate information services, women's empowerment, climate resilience, Ghana

1. Introduction

Nearly three-fourths of the 2.1 billion people living in extreme poverty depend on agriculture as their main source of livelihood (Lele and Goswami, 2021). Increasing frequency of extreme weather events such as droughts, floods, heat waves, and tropical storms due to climate change however poses multiple threats to agriculture. Recent global estimates indicate that about 91 percent of the 7,255 major disasters between 1998 and 2017 were driven by extreme weather events (Wallemacq and House, 2018). Such events adversely affect crop and livestock productivity, as well as farmers' willingness to experiment, invest, and innovate (Lybbert and Sumner, 2012). This jeopardizes food availability, incomes, and livelihoods, especially for the poor, smallholder subsistence farmers, and women (Tanner and Mitchell, 2008; Demetriades and Esplen, 2010; Thornton et al., 2014).

Governments and development agencies have sought to reduce the negative impacts of climate risks on vulnerable populations. They use a variety of approaches to manage weather risks *ex ante*, including the use of innovations aimed at building the resilience of the production systems against climate variability. Examples of these approaches include the provision of insurance against weather risks (Mahul and Stutley, 2010; OECD, 2015), promoting climate-smart agriculture (e.g., the use of sustainable and climate-resilient agricultural practices such as stress-tolerant varieties, conservation agriculture, and diversified farming), and climate information services [FAO (Food and Agriculture Organization of the United Nations), 2010; World Bank, 2011].

In developing countries, expenditure on agricultural innovation research increased by over 192 percent within the past four decades (Fuglie, 2016; Fuglie et al., 2020). Given that most developing countries have scarce resources, investments in agricultural innovations to build resilience compete for funds with other important areas of development such as social protection, health care, education, and physical infrastructure. Therefore, a better understanding of the different types of costs and benefits associated with developing and implementing these innovations will be critical to help justify, prioritize, and improve investments in them, as well as investments in the agricultural research-for-development that leads to these innovations.

Benefits associated with the innovations can be heterogeneous, and depend for instance on a user's gender, social class, or marital status. It is important to quantify benefits for different groups of farmers (such as women and poorer subsistence farmers). This will help identify target groups where the greatest potential welfare gains can be achieved, as well as adjust programming to create greater benefits for those groups that development practitioners are aiming to benefit most. This paper provides a framework for analyzing the costs and benefits of investments in agricultural innovations that aim to enhance the resilience of smallholder farmers in developing economies, allowing the estimation of heterogeneous benefits for various groups of beneficiaries.

A growing literature has been devoted to studying the costs and benefits of investments in various agricultural innovations; for instance, climate-smart agriculture (Marta-Pedroso et al., 2007; Balmford et al., 2011; Sain et al., 2017; Nganga et al., 2017a,b; Wafula et al., 2018; Mutenje et al., 2019; CARE-Burundi, 2020; Williams et al., 2020), and country-level rought insurance (Clarke and Vargas Hill, 2013; Jensen et al., 2017; Kramer et al., 2020). Many of these studies focus on quantifying the expected Net Present Value (NPV) of current and future cash flows generated by these innovations over their lifecycle; often discounted at market interest rates to estimate the costs, benefits, and the subsequent payback period of the investments.

Although the NPV approach adequately captures changes in expected cash flows, the approach does not account for the benefits of reduced risk exposure for risk-averse farmers. Damba et al. (2021) and Smith et al. (2021) for instance acknowledge that while attempting to assess costs and benefits, they were confronted with challenges in measuring unintended outcomes as a result of the usage of a particular technology. Jensen et al. (2017) go a step further, by quantifying the welfare benefits from improved consumption smoothing and the benefits of reduced risk exposure for risk averse farmers. They employ an expected utility model to compare the benefits from agricultural insurance and unconditional cash transfers among livestock farmers in Kenya. While serving as an important starting point, this study does not identify benefits related to the impacts of insurance and cash transfers on time use, which is an area where this paper contributes.

Moreover, it is important to understand the intrahousehold gendered distribution of costs and benefits (Kabeer, 1992), since spouses are likely to have conflicting preferences [such those described in Haddad et al. (1998), Donni and Chiappori (2011), and Doss (2013)]. Mutenje et al. (2019) and CARE-Burundi (2020) study gender as part of their cost–benefit analyses but do not quantify welfare gains from improved gender outcomes such as women's empowerment, which is another area where this paper aims to contribute. Most importantly, most existing gendered cost–benefit analyses are conducted at the household level, treating the household head's gender as the main variable for gender-disaggregated analyses. Given that most women live in male-headed households, and the fact that bargaining power will vary among women living in male-headed versus female-headed households, focusing only on the household head will likely bias the gender distribution of cost and benefits of agricultural innovations.

To address these gaps, our toolkit employs an expected utility framework to map individual consumption under alternative weather scenarios into a measure of wellbeing ('expected utility'), taking into consideration not only the expected level of consumption but also higher moments of its distribution, including its variance. In this way, the framework can capture the utility benefits associated with an improved ability to manage agricultural risks and smooth consumption, which is often an important objective for innovations developed to improve smallholder farmers' resilience. We extend this model to include leisure, to capture an innovation's benefits in terms of reducing labor burdens, or costs in terms of increasing workloads. Moreover, by using a non-unitary household model that allows for variations in individual bargaining power (Chiappori, 1988, 1992) we measure how the costs and benefits are differently distributed among men and women in the household. This will help in integrating the consequences of agricultural innovations related to gender equality and empowerment into a cost–benefit analysis.

To illustrate the use of the framework, we focus on climate information services (CIS) promoted through the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) program. AICCRA is a three-year World Bank funded program that aims to scale innovations from international agricultural research in six countries in Africa: Ethiopia, Kenya, Ghana, Senegal, Mali, and Zambia.[1] This study uses baseline data collected from 661 farmers recruited to participate in AICCRA's CIS program in Ghana. We first study how the use of CIS is associated with agricultural outcomes (including investments in farm inputs, agricultural productivity, and off-farm labor incomes) under three weather conditions: normal, moderate, and severe[2]. We then estimate the expected utility with and without CIS for different household members, taking into consideration their individual beliefs and preferences. To shed light on the intrahousehold distribution of costs and benefits related to CIS, we analyze utility gains separately for three types of individuals: men in male-headed households (MHH), which are typically the male heads themselves; women in MHH, which are typically the spouses of the male heads; and women in female-headed households (FHH),

1 More details on the AICCRA program can be found here: https://aiccra.cgiar.org/

2 Normal: the weather outcome is above the medium historical ranges; Moderate: weather outcome within the medium of historical ranges. Severe; current weather significantly below or way above historical ranges, such as severe drought or floods.

including widows and never married female heads with no primary male-decision maker within the household.[3]

We find that under moderate weather conditions, CIS users invest significantly more in farm inputs than non-CIS users and agricultural payoffs are significantly higher under CIS production regime. On average, for a risk-averse farmer, using CIS increases the expected utility by 37 percent. Compared to women in MHH, men have higher bargaining power, which significantly increases their level of consumption, and thus their expected utility. Female household heads have higher levels of consumption than individuals in MHH under normal weather conditions but consume less under severe weather conditions. These findings suggest that although women in FHH have the bargaining power to make decisions, they might lack adequate access to resources to cope with severe climate events. Women in MHH are the least empowered, with significantly lower levels of consumption, and expected utilities, and they draw the least benefits from CIS. Whereas investing in CIS would create a utility gain that is equivalent to an increase in consumption of 93 USD for male household heads, the gains for women are 76 and 65 USD depending on whether they reside in a FHH or MHH, respectively. These findings show how household-level analysis can mask important details regarding the intrahousehold distribution associated with costs and benefits from agricultural innovation.

The remainder of the paper is structured as follows. In Section "Background on Climate Information Services (CIS)", we provide background on CIS to contextualize the proposed framework to conduct cost–benefit analysis of resilience-enhancing agricultural innovations. This framework is introduced in Section "A new approach for cost-benefit analysis of resilience-enhancing innovations", along with the data needed to apply this approach. Section "Empirical application of the new approach for cost-benefit analysis" presents our empirical case study, and Section "Discussion and Conclusions" concludes.

2. Background on climate information services

CIS delivers data, statistical analyses, tools, and other information resources about expected future climate conditions – including, among others, temperature and precipitation scenarios, and sea-level changes – and their potential impacts on livelihoods (USAID, 2013). People and organizations can use this information to reduce climate-related losses and in building resilience to future climate risks. In agriculture, CIS enables farmers to optimize many aspects of their production systems, including the timing of sowing, planting, fertilizer application, irrigation, pest and disease control, harvesting, and post-harvest handling (Balaji and Craufurd, 2011; Hansen et al., 2011; McKune et al., 2018), enabling them to improve their farm productivity and welfare (Naab et al., 2019; Vaughan et al., 2019; Nidumolu et al., 2020).

CIS have several desirable attributes that make them attractive to policymakers and farmers. First, CIS increase the accuracy and reliability of weather forecasts, enabling farmers to make timely production decisions (Asrar et al., 2020). As such, CIS can have important labor-and gender-related outcomes. For instance, early drought warnings and weather forecasts can help farmers optimize when to plant their crops, thereby reducing the labor burden of having to plant a second time in case the rains fail (Gumucio et al., 2020). Second, communication and dissemination of CIS can be conducted through a diverse suite of freely available or cheap channels such as mobile phones (SMS, phone calls, and internet), radio, television, printed media, extension officers (through demonstrations, training, and visits) and other channels like public meetings, farmer-to-farmer messaging, and workshops (Yegbemey and Egah, 2021). This can improve affordability and equity in reach among various groups of farmers. Third, CIS can be easily tailored to meet the needs of different groups of farmers, and compared to other risk-management strategies, the marginal cost of CIS dissemination and scaling is low (Tall et al., 2014; Guido et al., 2020).

Although these advantages are broadly acknowledged, and several studies have found that farmers have a high willingness to pay for CIS (Ouédraogo et al., 2018; Dinh, 2020; Gitonga et al., 2020; Antwi-Agyei et al., 2021a), in many developing countries, especially those in sub-Saharan Africa, CIS is either missing or it is available as short-term weather and seasonal forecasts rather than user targeted large-scale national and regional information that can support long-term planning (Hansen et al., 2011; World Meteorological Organization, 2014; Georgeson et al., 2017). Moreover, women and poor subsistence farmers—who are disproportionately vulnerable to the negative effects associated with climate risks— are more likely to be excluded from available CIS (Beuchelt and Badstue, 2013; Huyer et al., 2017; Diouf et al., 2019; Antwi-Agyei et al., 2021b). Although CIS, if reaching these populations, could contribute to their empowerment, the information might not reach them, and in fact, providing CIS could widen information gaps relative to the groups that are not reached by CIS. The disempowering effect of this widening information gap is one potential cost of CIS. Moreover, if households choose to expand their agricultural production in response to having access to CIS, the additional labor associated with that expansion might disproportionally fall on women. It is therefore important to document the unintended consequences of CIS for different household members' work burdens as another potential cost of CIS.

The Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) program bridges these gaps by strengthening and facilitating the institutional capacity to develop and disseminate tailored and targeted CIS packages for small-scale farmers. The targeted CIS packages are expected to increase reach to previously excluded populations such as women and subsistence farmers. AICCRA also aims at promoting the delivery of longer-term forecasts that could help farmers in strategically planning their agricultural production activities. An important objective for AICCRA is also to document the impacts of these CIS packages, and their costs and benefits, including the costs associated with potential unintended consequences on for instance women's economic empowerment and work burdens.

Figure 1 provides an overview of how access and use of CIS intersect with resilience to weather risks and the potential costs and benefits associated with CIS use. By gaining improved access to information about effective climate response measures, farmers will be able to better anticipate climate-related events and take preventive

3 For the analysis, we classify self-identifying female heads with a male partner who is a key decision maker within the household as women in MHH.

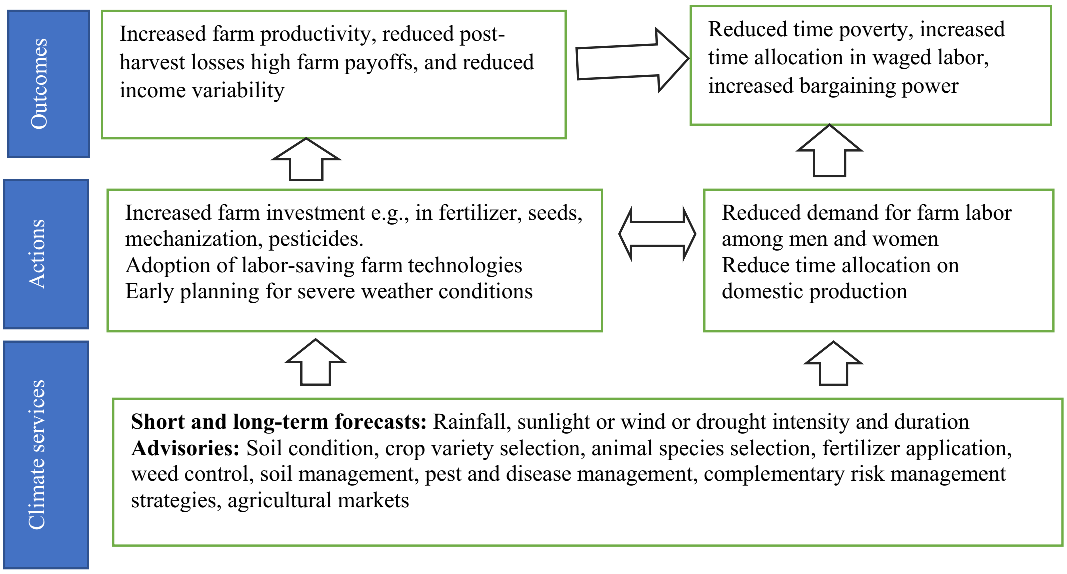


FIGURE 1
Linking CIS to climate resilience (source: Authors' depiction).

actions that can help safeguard productive activities, avoid catastrophic losses, and increase return on their investments in farm inputs, land, and labor. For instance, CIS can allow farmers to plant varieties that are optimal for the projected weather conditions, or they could increase their risk-taking capacity and invest in complementary inputs such as fertilizer, labor, and mechanization. These actions can directly impact farm productivity and incomes, thus improving household welfare. CIS could also shift labor burdens for women and men. For instance, CIS can reduce workloads via mechanization, better division of labor, or early planning, which can enhance individual and household welfare. This can also increase an individual's bargaining power, but potentially at the expense of others' say in how household resources are allocated. If CIS empower groups of individuals that are currently disempowered, net benefits from providing CIS are likely to be positive. But CIS could also empower already more powerful individuals, which may come at a cost of further disempowerment of marginalized individuals. Furthermore, a recommendation to apply fertilizer or grow new crop varieties may call for increased weeding and post-harvest processing, which can worsen labor burdens for household members (often women) who are tasked with these types of activities (Walker, 2013; Beuchelt, 2016). This would be a cost associated with the use of CIS.

3. A new approach for cost–benefit analysis of resilience-enhancing innovations

3.1. Theoretical framework

We model the costs and benefits associated with CIS from a farming household's perceptive using a collective household utility framework (Chiappori, 1988, 1992; Browning et al., 2014), which we extend to include multiple states of the world, or weather realizations. Under this framework, household utility is defined as a weighted average of the set of (potentially unequal) levels of expected utility for individual members, aggregated using these family members' bargaining weights (Sen, 1984). Most consumption takes place within the household, based on a common budget that is shared within the household.[4] Certain goods, such as food consumption, are rival private goods, while others, such as house improvements, are non-rival public goods. When choosing to allocate a limited budget to various private and public goods, the household takes into consideration utility outcomes of each member, weighted by that member's bargaining weight.

For simplicity, we model a two-person household with individuals $k \in \{1,2\}$, and assume that the household optimizes an aggregate of expected utility for both individuals, weighted by each individual's negotiation power or bargaining weight ω_k, where $\sum_{k=1}^{2} \omega_k = 1$ (Manser and Brown, 1980; McElroy and Hornery, 1981; Chiappori, 1988),

$$\max_{C_k, R_k} EU = \sum_{k=1}^{2} \omega_k EU_k\left(C_k, R_k, \gamma\right) = \sum_{k=1}^{2} \omega_k \sum_{\varphi=1}^{3} \varnothing_\varphi U_k\left(C_{\varphi k}, R_{\varphi k}, \gamma\right) \quad (1)$$

where EU is expected utility aggregated at the family level, $U_k(.)$ is individual k's utility function, γ denotes whether the household uses CIS $(\gamma = 1)$ or not $(\gamma = 0)$, C_k is the level of consumption for individual

4 We abstract from household members having individual, personal incomes, that they hide from their household members. There are cases where individual keep separate finances, however, whenever they both contribute to a household public good, they are regarded as deciding consumption jointly (Fafchamps, 2005).

k, and R_k is the amount of leisure that this person will enjoy.[5] Expected utility for individual k, $EU_k(\cdot)$, is an aggregate of individual utilities across three possible states of the world or weather realizations, $\varphi \in \{1,2,3\}$, using $\varnothing_\varphi$ as the probability of realizing weather event φ to aggregate contemporaneous utilities for the separate states of the world. We consider normal ($\varphi = 0$), moderate ($\varphi = 1$), and severe ($\varphi = 2$) weather events.

The household optimizes the level of consumption and leisure under weather realization φ for each family member k, subject to the budget and time constraints specified in Equations (1) and (2):

$$C_{\varphi k} = \omega_k Y\left(l_{\varphi 1}, l_{\varphi 2}, A_\varphi; \gamma\right) + w_{\phi k} Z_{\varphi k} \quad (2)$$

$$R_{\varphi k} = T - l_{\varphi k} - H_{\varphi k} - Z_{\varphi k} \quad (3)$$

The budget constraint, Equation (2), implies that an individual's consumption is determined by three variables: net household income from agricultural production, $Y(.)$, which is modeled as a function of both family members' labor allocation to farm activities, $l_{\varphi i}, i \in \{1,2\}$, and household investments in farm inputs, A_φ; the individual's share of that income, which is determined by that individual's bargaining weight, ω_k; and the individual's income from other activities, such as employment, casual work, and business, which is equal to the wage rate for those activities, $w_{\phi k}$, times the total number of hours worked on other activities, $Z_{\varphi k}$.[6] The time constraint, Equation (3), specifies the total amount of leisure that individual k enjoys as total available time minus any time spent on the farm, $l_{\phi k}$, on domestic work, $H_{\phi k}$, and other income-generating activities, $Z_{\phi k}$.

Note that the relationship between agricultural income and inputs ($l_{\varphi 1}, l_{\varphi 2}, A_\varphi$) depends on whether the farmer uses CIS to optimize its farming practices and technologies, γ. Using CIS could improve the return on labor, on farm inputs, or on a combination of the two, and in our framework, that is the only mechanism through which CIS use can influence utility.[7] In principle, one could also let the bargaining weight, ω_k, depend on whether the household uses CIS, given that information can be empowering and increase bargaining weights, but we abstract from doing so in this paper. As a result, we can quantify the utility gains from using CIS within this framework by defining a monetary equivalent M_k of utility gains from using CIS. This equivalent is implicitly defined in Equation (4) as the amount by which individual k's consumption would need to increase in the absence of CIS, $\gamma = 0$, to match this same person's expected utility when using CIS, $\gamma = 1$:

$$EU_k\left(C_k, R_k; 1\right) = EU_k\left(C_k + M_k, R_k; 0\right) \quad (4)$$

To make the framework more flexible and easily adaptable, we will implement a numerical approach to identify this amount M_k, instead of providing an explicit solution for the monetary equivalent of utility gains from using CIS. This numerical approach requires specifying a functional form for the utility function, for which we draw on Rupert et al. (1995):

$$U(C,R) = \frac{1}{\alpha} \cdot \frac{\left(\alpha C^\rho + (1-\alpha) R^\rho\right)^{\frac{1-r}{\rho}}}{1-r} \quad (5)$$

Here, we define α as the contribution of consumption to an individual's utility (relative to the contribution of leisure), r as the coefficient of relative risk aversion, and $1/(1-\rho)$ as the elasticity of substitution between consumption and leisure. This functional form may be a simplification of reality, as it assumes full separability and a constant elasticity of substitution (CES) between consumption and leisure, but it offers a useful starting point to quantify changes in expected utility when a program may affect both consumption and time use.[8]

3.2. Data requirements

To apply this framework, one needs data on the variables and parameters included in Equations (1)–(5). In this subsection, we outline what types of data one could collect to satisfy these data requirements. This includes various household and individual attributes such as the distribution of weather outcomes, farmers' demographic and socio-economic characteristics, climate risks, CIS access and use, consumption, leisure, and time and risk preferences.

3.2.1. Probability of weather outcomes

The information on weather probabilities can be elicited by directly asking the respondents about their perception on the occurrence of severe, moderate, or normal weather condition within the next 10 years, such that the subjective probabilities of these events occurring sum to one, $\sum \varnothing_\varphi = 1$. The problem with this approach is that it is hypothetical, which will not always elicit truthful responses. It also provides merely a course measure, given that this method

5 Utility $U_k(.)$ is continuous, increasing (>0)-->$U_k' > 0$), twice differentiable and strictly concave (<0)-->$U_k''(.) < 0$). Note that preferences can vary across family members, since individuals have separate utility functions.

6 Note that income from agricultural production is used to invest in agricultural inputs, which are considered household public goods, and the remaining is spent on individual consumption, which is considered a rival good.

7 Instead of specifying a functional form for the production function and estimating how CIS affects the return of net agricultural income, $Y(.)$, on labor and farm inputs, we estimate gains from CIS directly from empirical observations of net agricultural income without and with CIS, not accounting for labor and farm input use. The framework could be extended in cases where rich panel data allow estimating production functions, and the Appendix conceptualizes one way to model the impacts of CIS. It suggests that under normal weather conditions, farmers are expected to do equally well regardless of whether they use recommendations made by CIS; during severe weather conditions, farmers are likely losing most of their income, regardless of whether they are following CIS recommendations; and only during moderate weather conditions, CIS may make a real difference, protecting farmers' livelihoods from negative shocks.

8 Moreover, the numerical approach is sufficiently flexible for someone to specify an alternative utility function when applying the framework in cost–benefit analyses.

allows to construct probabilities only in increments of a decimal. In case researchers are interested in averages across a population, this will not necessarily be an issue, given that unsystematic biases in individual responses disappear when aggregating over larger numbers of survey respondents, and this will also provide more exact probabilities than the individual estimates with increments of at most a decimal (0, 0.1, 0.2, etc.). Alternatively, if an individual's subjective beliefs are an important outcome measure on their own, one can use more granular and incentivized methods to elicit beliefs (see Attanasio, 2009, for an overview).

3.2.2. Distribution of consumption and leisure across weather scenarios

We define consumption as the expenditure incurred on goods and services (such as food, health, clothing, education, among others) that are used for the satisfaction of needs or wants (OECD, 2015). Current practices for collecting consumption data differ widely across types of surveys, between countries, and over time, which might compromise the comparability of the data and measurement (FAO and World Bank, 2018). One can measure consumption through an expenditure approach, but this is typically a time-consuming endeavor. Instead, in this study, where we needed to rely on a short survey, we assume that household and individual consumption growth is correlated very closely with expected income growth (Skinner, 1987; Jappelli and Pistaferri, 2000; Howe et al., 2009) and use projected incomes as a proxy for consumption. Several approaches to collecting income data have been outlined in the literature (for example, Sweeney et al., 2016). In this study, for each of the three alternative weather scenarios, we ask respondents to report the minimum and maximum projected incomes from agriculture, including crop production, livestock, and livestock activities ($Y(.)$ in our framework), as well as from waged, salaried and trade activities ($w_{\phi k} Z_{\varphi k}$ in the framework). Income under each weather scenario is then estimated by averaging over the two values to reduce measurement error compared to using a single value response of projected income.

Following Alderman and Sahn (1993) and Aguiar and Hurst (2007), we define leisure as time spent away from market and domestic work to pursue other activities designed to yield direct utility, such as entertainment, socializing, active recreation, and general relaxation (excluding maintenance activities such as sleeping and eating). Leisure is an important aspect for individuals as it improves social well-being and long-term productivity (Beatty and Torbert, 2003; Wei et al., 2016). To estimate the share of time dedicated to leisure, it is important to understand how individuals divide their 24 h among various daily activities, for which we employ time-use survey guidelines from the Multinational Time Use Survey Project.[9] We ask individuals to report the average time spent on various activities within a day, including paid work (such as full-time and part-time jobs, commuting to the workplace, school activities among others), domestic work (such as cooking, cleaning, caring for children and other family members, volunteering, shopping among others), farm work (such as planting, weeding, fertilizer application, harvesting, post-harvest handling, marketing among others), personal care (sleep, eating and drinking among others), and leisure (such as pursuing hobbies, watching television, socializing with friends and family, attending events, among others). One can deduce leisure time from the amount of time an individual engages in other non-leisure activities.

We ask respondents to provide their time use profile under bad, normal and good weather realizations, but when someone has longitudinal panel data with variation in weather realizations over time, one could use a 24-h time use profile, and estimate how this time use profile depends on realized weather outcomes, since a 24-h time use profile reduces measurement errors on time use responses.

3.2.3. Risk preferences

Risk preferences (r in our conceptual framework) are an important factor in individual decision making on investment, asset valuation, and life choices. For risk averse farmers, utility gains can be obtained not only from increases in the *levels* of consumption and leisure, but also from a reduction in the *variability* of these two variables. For a given consumption and leisure level, utility gains from reduced risk will be greatest among farmers with higher levels of risk aversion. It is therefore important to also capture risk preferences.[10]

To date, there have been several approaches used to assess individual degree of risk aversion. For instance, Binswanger (1980) uses lottery choices from field experiments to show that most farmers exhibit a significant degree of risk aversion. Other methods include a bidding and pricing task (Smith and Walker, 1993), and eliciting buying and/or selling prices for simple lotteries (Kachelmeier and Shehata, 1992). We adopt a risk preference elicitation method first introduced by Eckel and Grossman (2002) and validated by Falk et al. (2018) in the Global Preference Survey.[11] In this approach, respondents make hypothetical choices between five lotteries with different levels of risk and expected payoffs versus a safe option. Measures of risk aversion are inferred from the levels of risk and expected payoffs in the lotteries at which respondents switch from preferring the lottery to the safe option.

3.2.4. Bargaining weights

An individual's bargaining power, ω_k, will influence the share of rival household resources allocated to them, which will in turn influence their utility outcomes (see Equations 1 and 2). This implies that the intrahousehold distribution of rival resources will favor the preferences of the spouse with a stronger bargaining weight. Existing literature presents several ways to measure individual bargaining power, including the use of consumption ratios for different household members, income contribution, educational attainment, inheritance, and asset ownership rights (Blumberg and Coleman, 1989; Friedman-Sanchez, 2006; Anderson and Eswaran, 2009). Manser and Brown (1980) and McElroy and Hornery (1981) suggest that an individual's bargaining power depends on a threat point, that is, when negotiating, spouses can threaten to walk away, and therefore bargaining power is related to how much utility an individual can achieve on their own. Friedberg and Webb (2006) however argue that several omitted factors in the previous empowerment measures could bias the outcomes. For instance, if a spouse earns more because they work more, this might

9 https://www.timeuse.org

10 In our conceptual framework, we treat access to CIS as an exogenous parameter, but in reality, farmers' willingness to use CIS and their ability to draw benefits from it will depend on their degree of risk aversion, offering another reason for why it is important to capture baseline levels of risk aversion.

11 https://www.briq-institute.org

reduce the time that is available for them to engage in daily decisions making activities, rendering them disempowered. They therefore argue that it is better to construct measures of bargaining power based on questions that directly ask respondents about how major decisions are made within their households.

To measure individual bargaining power, we follow the approach described in Friedberg and Webb (2006) and develop an index based on who has 'the final say' between a husband and wife (or opposite sex adult decision-makers) when major decisions are being made. We follow the bargaining power indicators outlined in the "input in productive decision-making" module of the Women's Empowerment in Agriculture Index (WEAI; Alkire et al., 2013). In the module, respondents were asked whether they participated in decision making regarding various household activities, and if they participated, to what extent they had an input, and whether they could make the final decision. These household activities included seed selection, land allocation to various farm activities, harvesting, rearing of small and large livestock, household engagement in waged and salaried labor, and household spending. Our measure reveals whose preferences are reflected to a greater degree in household choices. By directly eliciting decision-making power, our analysis overcomes potential omitted variable bias problems arising in earlier studies.[12]

4. Empirical application of the new approach for cost–benefit analysis

4.1. Sampling and data collection

To demonstrate the applicability of our framework, we use survey data collected from the AICCRA intervention communities which constitute 6 regions in Ghana. The AICCRA intervention is a continuation of an earlier CIS program implemented by the CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS). The data is from a baseline survey from 651 households conducted in November 2022. The sampling procedure involved a multi-stage purposive sampling criteria whereby six regions (namely, Bono East, Central, Greater Accra, Northern, Upper East, and Upper West) were selected for the study based on population size, agricultural activities, and climate risks. Using the same criteria, a minimum of one and maximum of three districts were chosen from each region, making a total of 11 districts. In total, 38 villages were randomly selected from all the districts. Sampling was clustered at the village level: in each village, a sampling frame was developed with the help of community leaders, from which households were randomly selected for inclusion in the study. The village also served as clusters for treatment randomization, whereby 19 villages were allocated to the treatment and 19 to control. The data used in this paper were collected as baseline, before the CIS intervention was rolled out in the 19 randomly selected treatment villages.

4.2. Summary statistics

4.2.1. Household characteristics

Table 1 provides descriptive statistics for the full sample (Columns 1–2) as well as for CIS users versus non-users (Columns 3–4 and 5–6, respectively), and the difference between the two (Column 7). In total, 61 percent of all households have been using CIS prior to the survey. The average age of the household head is 45 years and 67 percent of households are male headed. A significantly higher proportion of male-headed households used CIS. The average respondent has completed 3.63 years of formal schooling, with CIS users having significantly higher education levels than non-users. About 49 percent of the households belong to a farmer's club and 15 percent are part of a savings group.

Households derive about 65 percent of their income from crop farming, indicating that this is their main but not only source of livelihood. However, CIS users depend significantly more on crop production than non-users, earning close to 70 percent of their income from crop farming. About 16 percent of the household income is derived from livestock farming. CIS non-users depend significantly more on livestock than CIS users. About 82 percent of farmers produced maize during the short rains of 2022, indicating the importance of maize to both CIS users and non-users. Other crops produced include cowpeas, potatoes, yams, pepper, and tomatoes. CIS users are significantly more likely to grow potatoes, yams, and pepper. In the first half of 2022, about half of the households in the sample experienced shocks that prevented them from sowing, or that prevented the germination of their seeds. Farmers also reported shocks that caused crop damage (44 percent), post-harvest losses (20 percent) and livestock deaths (17 percent). Most of these shocks are experienced equally often by CIS users and non-users, but households not using CIS are significantly more likely to experience post-harvest losses.

We also elicited the probability at which different types of weather scenarios occur, to be able to estimate expected utility by aggregating utilities for each of the three weather scenarios [$\varnothing_{\varphi}$, see Equation (1)]. We did this by asking households to indicate how many of the next 10 years they expected to have severe, moderate, versus normal weather conditions. We then divided their responses to these questions by 10, in order to derive an individual's estimate of the probability that the different types of weather conditions would occur. On average, households expect severe, moderate, and normal weather conditions with a probability of 37, 31, and 32 percent, respectively. Importantly, this did not vary between CIS users and non-users, and thus, when estimating expected utility, we will use the same beliefs for the two household types.

4.2.2. CIS use

Figure 2 shows the distribution of topics on which the 402 households using CIS received information through a CIS program.

12 The drawback of the model used, and its solution in which consumption out of household-level net income is equal to total income times the individual's bargaining weight, is that bargaining weights need to sum to one. This means that an increase in bargaining power of one family member comes at the expense of reduced utility for another household member, unless the change in bargaining weights was accompanied by an increase in net income. This zero-sum game is against the idea of many empowerment programs that they are creating win-win solutions. Thus, we see the collective household bargaining model as a useful starting point, but future research could explore alternatives to circumvent the condition that bargaining weights need to sum up to one.

TABLE 1 Household characteristics disaggregated by CIS use.

	Aggregate		Used CIS		Did not use CIS		Diff
	Mean	SD	Mean	SD	Mean	SD	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Socio-economic and demographic characteristics							
Age of household head	45.30	12.99	45.33	13.18	45.23	12.67	0.10
Gender of household head (male = 1)	0.67	0.47	0.71	0.45	0.60	0.49	0.11**
Education level (years)	3.63	3.19	3.93	3.21	3.14	3.08	0.78**
Membership to farmer's club	0.49	0.50	0.47	0.50	0.51	0.50	−0.04
Membership to a livestock group	0.03	0.16	0.025	0.16	0.03	0.17	0.01
Membership to a savings group	0.15	0.36	0.16	0.37	0.14	0.35	0.02
Proportion of income from crops	0.65	0.36	0.70	0.35	0.56	0.36	0.14***
Proportion of income from livestock	0.16	0.24	0.13	0.23	0.20	0.27	−0.07*
Crops planted in 2022							
Maize	0.82	0.38	0.83	0.11	0.80	0.40	0.04
Cowpea	0.17	0.38	0.16	0.37	0.18	0.38	−0.02
Potatoes	0.03	0.17	0.05	0.21	0.01	0.09	0.04**
Yams	0.23	0.42	0.28	0.44	0.15	0.36	0.12***
Pepper	0.13	0.34	0.17	0.37	0.07	0.25	0.10***
Tomato	0.10	0.30	0.10	0.30	0.09	0.29	0.01
Experienced shock that							
Prevented sowing/poor germination due to drought/extreme weather	0.51	0.50	0.51	0.50	0.49	0.50	0.01
Caused damage to crops	0.44	0.50	0.47	0.50	0.39	0.49	0.08
Post-harvest crop losses	0.20	0.40	0.16	0.37	0.27	0.44	−0.11**
Caused livestock death/disease	0.17	0.37	0.17	0.38	0.15	0.36	0.01
Probability of weather outcome for the next ten years							
Severe weather	0.37	0.17	0.36	0.16	0.37	0.18	−0.01
Moderate weather	0.31	0.12	0.32	0.12	0.30	0.12	0.01
Normal weather	0.32	0.14	0.32	0.13	0.33	0.15	0.00
Observations	661		402		259		

Column (7) provides the difference in means between respondents that "Used CIS" and those that "Did not Use CIS." We test for significant differences between those two groups using a *t*-test. ***$p < 0.01$; **$p < 0.05$; *$p < 0.10$.

Information on expected rainfall, including intensity and duration of rainfall, is the most commonly used form of CIS, followed by information on recommended planting time, crop variety selection, and fertilizer application. Advisories on water management, field selection, weed management and soil management are used less frequently.

4.2.3. Bargaining power

Figure 3 shows the distribution of household bargaining power among the three gender categories. As discussed, in the theoretical model bargaining weights are distributes across the primary and secondary decision maker within the household such that $\sum_{k=1}^{2} \omega_k = 1$. Even in FHH, where there is only one decision maker on whom the survey was administered, other family members or community neighbors, may have influence in the decision-making process. A woman in a FHH will therefore not necessarily have a bargaining power that is equal to one. But given that we are defining ω_k at the household decision-making level, we maintain bargaining power for FHH at 1. In MHH, with both primary male and secondary female decision makers, Figure 3 shows that male household heads have substantially higher levels of bargaining power compared to their spouses $(p < 0.01)$. The lower levels of bargaining power among women living in MHH is an indicator of their level of disempowerment and shows how household negotiations and allocation of household public goods might not favor them.

In theory, CIS could have impacts on bargaining power, as it can provide family members with information that increases their influence in household decision-making. However, we do not find significant differences in bargaining power between CIS users and non-users in either of the three groups (results not shown here but available upon request). This means that in the empirical application of our framework, we are unable to quantify utility gains related to married women's increased bargaining power, but in other settings, where CIS users may enjoy increased bargaining weights, and a redistribution of resources within the household, our expected utility framework could be used to quantify the related utility costs and benefits.

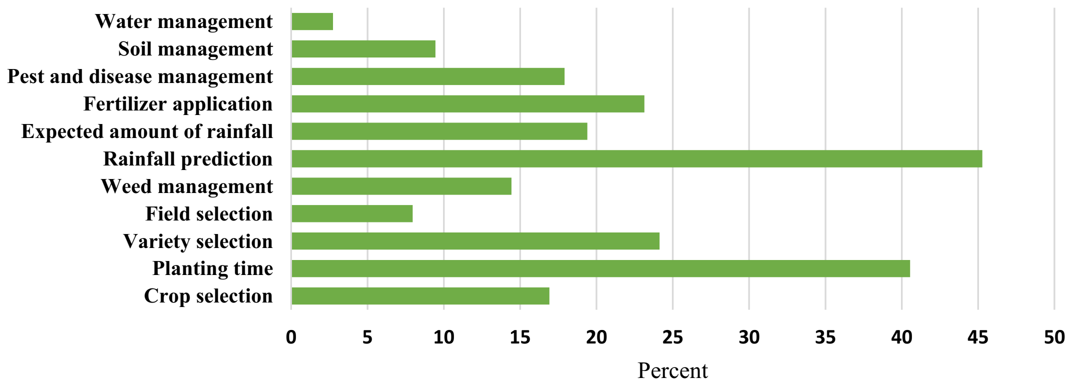


FIGURE 2
Household CIS use.

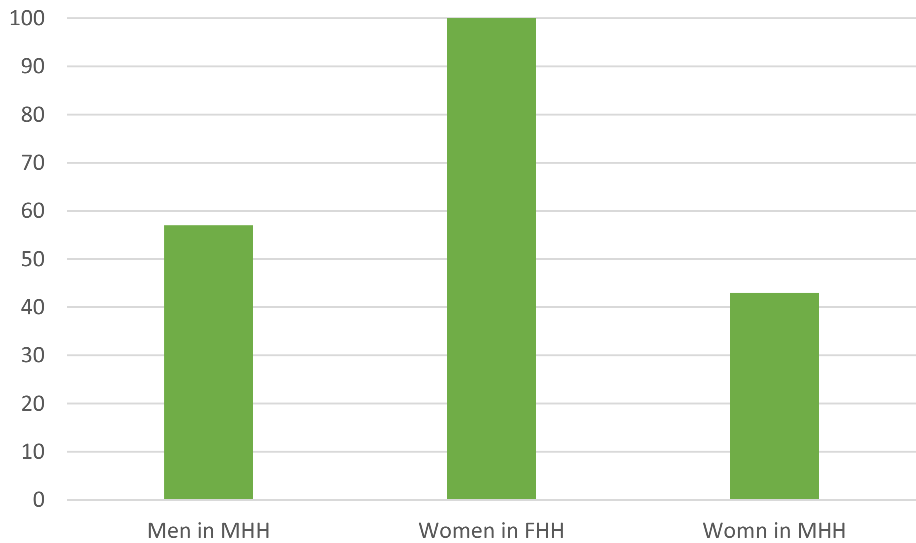


FIGURE 3
Distribution of household bargaining power. MHH and FHH stands for "Male Headed Households" and "Female Headed Households" respectively.

4.3. Investments, labor allocation, and household incomes by weather scenario

In this section, we describe the main variables that enter the budget constraint (Equation 2), including net agricultural household income, household farm investment, and labor allocations under CIS and non-CIS production regimes. Table 2 indicates the average farm investment for CIS users and non-users (A) in Ghanaian Cedi under different weather scenarios and the expected expenditure estimated as $\sum_{\varphi=1}^{3} \varnothing_{\varphi} A_{\varphi}$. The results show that the largest share of farm investment across the different weather outcomes is allocated toward fertilizer, hired human labor, seeds, herbicides, and mechanization. We find that when farmers are expecting severe weather outcomes, CIS users invest significantly more in pesticide, herbicides, machinery, and hired labor. CIS users also invest significantly more in seeds, fertilizer, pesticides, herbicides, machinery, and labor under moderate and/or normal weather conditions. Although farmers in both production regimes have low investment in animal traction and agricultural insurance, compared to CIS users, CIS non-users invest significantly more in animal traction under severe and moderate weather outcomes and they purchase significantly more agricultural insurance under moderate and normal weather conditions.[13] Aggregating across the three weather scenarios, CIS users expect spending significantly more on fertilizer, pesticides, herbicides, machinery, and hired labor than CIS non-users. This is attributed to well informed CIS available at various stages of a production season and the need to respond to the demands of the services accessed.

Table 3 shows the average daily time allocation (in hours) in various household activities under different production regimes and weather

13 Farmers may purchase agricultural insurance even in seasons with normal weather conditions because enrollment windows typically close at the start of the agricultural season.

scenarios, as well as the expected number of hours per day, aggregating over the three weather scenarios (for instance, $\sum_{\varphi=1}^{3} \varnothing_{\varphi} l_{k\varphi}$ in the case of on-farm labor). We include activities related to crop production (including grain production and production for high-value markets such as horticultural farming) and livestock production (including small and large animal farming, and aquaculture). Households also reported the amount of time they spend on non-farm domestic work (including time spent on cooking, fetching water and firewood, providing unpaid care work such as taking care of the elderly and children), market activities (including salaried and waged employment, and business), and leisure activities (including travel personal care, exercising, or socializing; but excluding maintenance activities such as sleeping and eating). The latter is used to construct the amount of leisure that individual household members experience ($R_{\varphi k}$ in Equation).

Under the three weather conditions, we find that respondents from households not using CIS allocate significantly more time to livestock production and domestic activities while CIS users allocate significantly more time to market activities. There were no statistical differences in the time allocation to crop production and leisure between CIS users and non-users. Consistent with our theoretical assumption, the findings on significant differences in time allocation in domestic and market activities could signal that CIS can potentially free up time for users to pursue other market activities, but we do not replicate these findings in the labor domain.

We finally evaluate the differences in projected household income from agricultural activities, paid domestic work, waged and salaried employment, and other household businesses. Table 4 shows that projected agricultural incomes (both crop and livestock income) are highest under normal weather conditions and lowest under severe weather conditions. CIS users project earning significantly higher crop incomes under each of the three weather scenarios. This could be directly attributed to the preparedness that the CIS packages provide to the users which allows for planning of available resources and activities to mitigate negative climate events. At the same time, CIS users projected higher incomes from livestock and livestock activities which are significantly higher under moderate and normal weather scenarios. Consistent to time spent in market activities, projected business incomes are larger for CIS using households, however the differences are not statistically significant.

The results further show that CIS non-users project significantly higher levels of incomes from waged and salaried activities. Moreover, CIS non-users incomes from domestic activities are higher under all-weather scenarios, however the differences are not statistically significant. The findings on domestic and waged or salaried incomes suggest households that do not use CIS could be more diversified outside of farm production than their CIS counterparts. At the aggregate level, the difference in the expected level of income for CIS users versus non-users is 4,441 Cedis per season (387 USD). This is the increase in income that the typical CBA would report as the program benefit. Moving forward, we will analyze how this estimated benefit changes as we also consider time use and the intrahousehold distribution of benefits, and introduce a utility framework to analyze these benefits.

4.4. Consumption and leisure based on an individual's bargaining power

We apply the utility model described in Section "A new approach for cost-benefit analysis of resilience-enhancing innovations" to estimate the costs and benefits associated with CIS and their subsequent intrahousehold distribution. We begin by estimating individual consumption based on Equation 4, assuming that this is equal to $Y(.)$, agricultural income net of investments in agriculture (A_{φ}), multiplied by an individual's bargaining weight (ω_k), plus individual incomes from various market activities such that $C_k = \omega_k Y_{\varphi} + W_{\varphi k}$. Figure 4 shows that for all the three gender categories, consumption is highest under normal weather conditions,

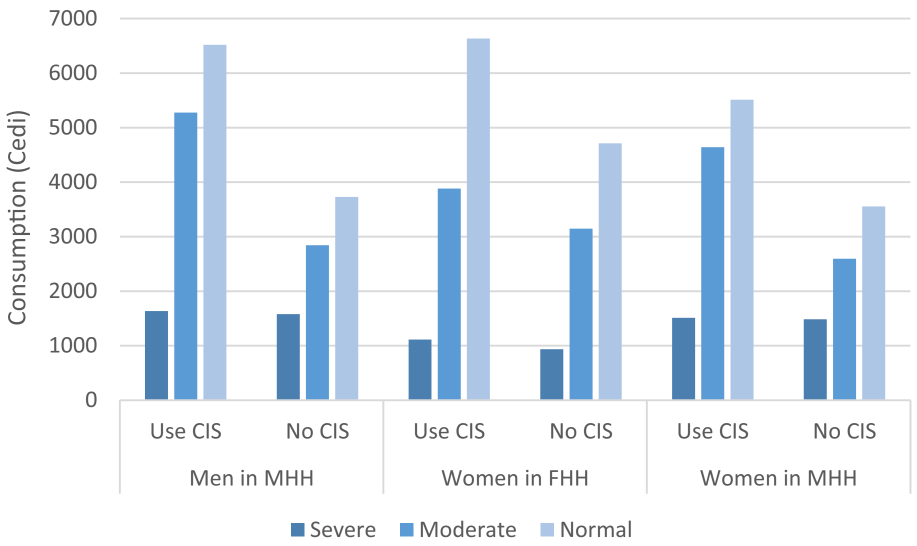


FIGURE 4
Intrahousehold distribution of individual-level consumption.

TABLE 2 Household investment on farm production conditional on CIS regime and weather outcome.

	Severe weather (φ^2)			Moderate weather (φ^1)			Normal weather (φ^0)			Expected expenditure		
	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Seeds	311	207	104	343	201	142	358	214	144*	336	207	128
	(1167)	(568)		(1304)	(570)		(1316)	(564)		(1228)	(557)	
Fertilizer	1,058	845	213	1,113	816	297*	1,151	858	293*	1,105	837	267*
	(1837)	(1214)		(1971)	(1149)		(21728)	(1167)		(1957)	(1152)	
Pesticides	159	80	79**	160	88	72**	156	84	72***	158	84	74***
	(383)	(147)		(385)	(159)		(375)	(165)		(374)	(150)	
Manure	31	27	4	31	30	1	32	36	−4	31	31	0
	(104)	(97)		(104)	(107)		(102)	(130)		(99)	(106)	
Herbicides	383	237	145**	442	248	194**	522	261	261**	446	248	197**
	(812)	(491)		(11362)	(493)		(1786)	(533)		(1209)	(492)	
Animal traction	10	40	−30*	11	30	−19*	13	30	−17	11	33	−22*
	(75)	(179)		(83)	(127)		(89)	(133)		(73)	(136)	
Machinery	423	267	157*	435	284	151*	438	296	142*	431	282	150*
	(1124)	(390)		(1115)	(389)		(11253)	(435)		(1117)	(405)	
Hired Labor	1,294	628	666***	1,559	623	936***	1748	702	1046***	1,521	651	871***
	(3555)	(1658)		(4904)	(1666)		(5606)	(1841)		(4521)	(1695)	
Animal fodder	42	49	−7	35	45	−10	37	44	−7	38	46	8
	(131)	(156)		(120)	(149)		(127)	(147)		(120)	(142)	
Ag. insurance	5	11	−6	6	20	−14*	5	21	−16*	5	17	−11*
	(41)	(68)		(48)	(101)		(45)	(103)		(120)	(142)	
# of observations	402	257		402	257		402	257		402	257	

Standard deviation in parenthesis. We test for significant differences between those two groups using a *t*-test. ***$p < 0.01$; **$p < 0.05$; *$p < 0.10$.

TABLE 3 Household labor allocation conditional in CIS regime and weather outcome.

Activity (hours/day)	Severe weather (φ^2)			Moderate weather (φ^1)			Normal weather (φ^0)			Expected labor allocation		
	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Crop production	4.37	4.47	−0.10	5.33	5.16	0.17	5.32	5.16	0.16	4.94	4.88	0.06
	(0.99)	(1.12)		(1.14)	(1.31)		(1.14)	(1.431)		(1.00)	(1.20)	
Livestock production	2.58	2.74	−0.16*	2.52	2.68	−0.16*	2.52	2.67	−0.15**	2.52	2.67	−0.17*
	(0.78)	(1.02)		(0.77)	(0.91)		(0.76)	(1.00)		(0.73)	(0.91)	
Domestic work	2.47	2.84	−0.37***	2.44	2.79	−0.35***	2.44	2.79	−0.35***	2.42	2.80	−0.37***
	(0.72)	(1.14)		(0.74)	(1.03)		(0.74)	(1.02)		(0.67)	(1.04)	
Market activities	2.76	2.34	0.42***	2.45	2.12	0.33***	2.45	2.15	0.28**	2.56	2.22	0.34***
	(1.41)	(1.25)		(1.23)	(1.21)		(1.24)	(1.21)		(1.24)	(1.18)	
Leisure	1.91	1.87	0.04	1.88	1.87	0.01	1.79	1.75	0.04	1.86	1.83	0.03
	(0.63)	(0.54)		(0.63)	(0.55)		(0.58)	(0.54)		(0.57)	(0.49)	
# of observations	402	259		402	259		402	259		402	259	

Standard deviation in parenthesis. We test for significant differences between those two groups using a *t*-test. ***$p<0.01$; **$p<0.05$; *$p<0.10$.

TABLE 4 Expected household incomes conditional on CIS production regime and weather outcome.

	Severe weather (φ^2)			Moderate weather (φ^1)			Normal weather (φ^0)			Expected incomes		
	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Crop	2,626	1,100	1518***	5,237	2041	3197***	8,479	3,435	5044***	5,305	2,138	3166***
	(4761)	(1636)		(9345)	(2835)		(15858)	(4847)		(9398)	(2928)	
Livestock	1,253	839	414	4,687	1,536	3151**	3,029	1760	1269**	2,885	1,349	1536**
	(4250)	(2990)		(5665)	(5584)		(12055)	(5607)		(6047)	(4577)	
Domestic work	91	198	−107	131	251	−120	182	260	−78	132	234	−101
	(538)	(1219)		(793)	(1383)		(1084)	(1425)		(755)	(1300)	
Waged/salaried	1,345	1,686	−341*	1,290	2027	−737**	1,230	2097	−867**	1,291	1923	−632**
	(5648)	(7559)		(5621)	(7977)		(5591)	(7846)		(5554)	(7653)	
Other business	981	690	291	1,038	940	98	2046	1,002	1,044	1,339	867	471
	(3777)	(3215)		(2928)	(3881)		(7551)	(4431)		(4437)	(3394)	
# of observations	402	259		402	259		402	259		402	259	

Standard deviation in parenthesis. We test for significant differences between those two groups using a *t*-test. ***$p<0.01$; **$p<0.05$; *$p<0.10$.

10.3389/fsufs.2023.1129419

and lowest under severe weather conditions. These results are not surprising considering the fact that farmers realize better agricultural payoffs under normal weather conditions even without CIS use. Households that use CIS under normal and moderate weather conditions realize significantly better $(p < 0.01)$ consumption outcomes than their non-CIS counterparts. Although the consumption of CIS using households is marginally higher under severe weather conditions, the differences are not statistically different.

At the individual level, we find that under severe and moderate weather conditions, men heads in CIS using households have better consumption outcomes than women in both categories. Women heads in CIS using household experience better consumption outcome under normal weather conditions, however, women heads in both CIS production regime have the worst consumption outcomes under severe weather outcomes. These findings suggest that even though women in FHH have the autonomy of decision making in their household, they might lack adequate access to recourses that can help them in coping with severe climate events. At the aggregate level, we find that women in MHH have the least consumption outcomes, which is directly attributable to their lower degree of bargaining power. Collectively, these results demonstrate that by failing to account for intrahousehold distribution of agricultural innovation benefits, most studies overestimate the benefits accruing to women.

Next, we estimate the intrahousehold distribution of leisure under the different weather conditions and CIS production regimes. Figure 5 shows the amount of leisure enjoyed by CIS users and non-users. Within each group (e.g., Women in FHH who use CIS), there were no statistically significant differences in leisure time. However, CIS non-users in male heads of households enjoy significantly more leisure time than women $(p < 0.05)$, while women in MHH, have the least amount of leisure under both production regimes. If CIS helps households free up time, as is often theorized (Gumucio et al., 2020), then it appears that in our study context, women did not use these time savings to enjoy more leisure time. Furthermore, the use of CIS did not decrease the labor burden borne by women living in MHH.

4.5. Estimating expected utility framework for different types of CIS users and non-users

To map these results into Equation (7), we first assume that the relative contribution of consumption and leisure to an individual's utility are equal to one another, that is, $\alpha = (1 - \alpha) = 0.5$. In an extension, one could use data on a farmer's willingness to substitute income for increased leisure (for which we have questions included in the survey described in Section "Data requirements") to calibrate this parameter, but the current analyses adopt this assumption to simplify the empirical illustration of the framework. For similar reasons, we follow Lim and Lee (2021) and Choi et al. (2008) by also assuming imperfect substitution between consumption and leisure among all individuals, and fixing $\rho = 0.05$. We use farmers' expectations of the frequency at which alternative weather conditions occur to estimate the probability of the occurrence of these weather scenarios, such that severe weather occurs with a probability $\varnothing_2 = 0.37$, moderate weather with a probability $\varnothing_1 = 0.31$, and normal weather with a probability $\varnothing_0 = 0.32$. To evaluate how expected utility with and without CIS varies in risk preferences, we present results assuming that a decision-maker is risk averse $(r = 0.5)$, risk neutral $(r = 2)$, or risk loving $(r = 3)$.

Table 5 shows the expected utility from consumption and leisure for the different groups of individuals under different weather scenarios for a risk averse farmer $(r = 0.5)$. For all individuals under consideration, the expected utility from consumption and leisure is highest under normal weather conditions, and lowest under severe weather conditions. We find CIS users attain higher levels of utility from consumption and leisure than CIS non-users. The differences are statistically

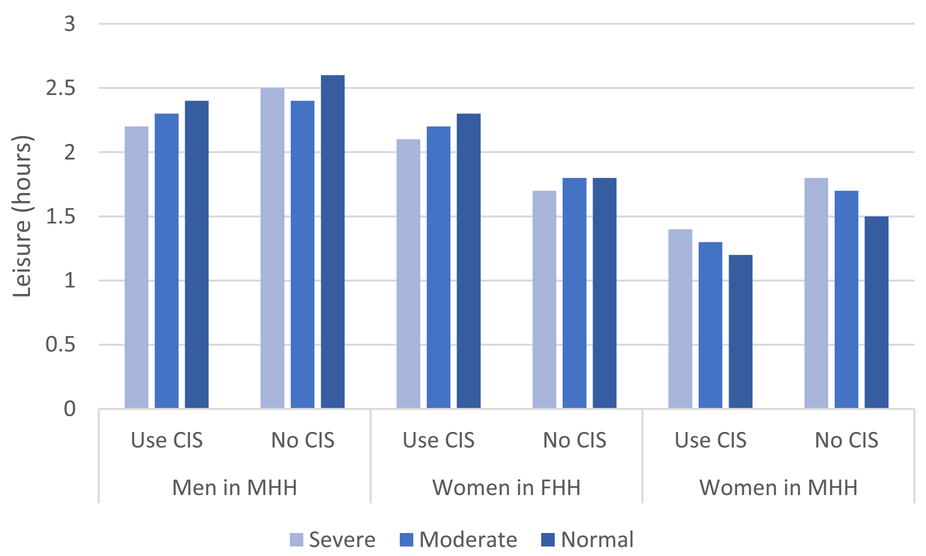


FIGURE 5
Intrahousehold distribution of leisure.

TABLE 5 Household utility conditional on CIS production regime and weather outcome.

	Severe			Moderate			Normal			Expected utility		
	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff	CIS	No CIS	Diff
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Men in MHH	84.55	61.40	23.15***	95.13	73.89	21.2***	106.10	78.21	27.89***	94.73	70.65	24.07***
	(42.75)	(40.56)		(52.82)	(50.07)		(53.32)	(49.55)		(49.25)	(46.38)	
Women in FHH	62.13	30.24	31.89***	61.36	32.43	28.92***	68.05	53.59	14.46***	63.79	38.39	25.39***
	(62.13)	(50.49)		(63.88)	(51.27)		(66.80)	(53.82)		(64.17)	(51.80)	
Women in MHH	41.07	28.20	12.86*	41.44	32.40	9.04	44.92	32.88	12.04*	42.42	31	11.42*
	(50.12)	(48.08)		(52.03)	(49.11)		(59.27)	(52.59)		(53.64)	(49.84)	
# of obs.	402	259		402	259		402	259		402	259	

Standard deviation in parenthesis. We test for significant differences between those two groups using a *t*-test. ***$p < 0.01$; **$p < 0.05$; *$p < 0.10$.

different under all-weather outcomes for household heads, and under severe and normal weather conditions for women in MHH. These results are consistent with the earlier findings that CIS use increases the level of consumption across all gender categories (Figure 6).

Comparing aggregate expected utilities across individuals in Columns (10)–(12), we find that on average, men heads of households under both CIS and non-CIS production regimes have the highest expected utility levels followed by women in FHH. On aggregate, women in MHH have the lowest levels of expected utility. Overall, we find that CIS use increases the expected utility from consumption and leisure by 37 percent.

Figure 6 shows the relationship between an individual's risk aversion and the expected utility from consumption and leisure. Expected utility increases with an increase in the degree of risk-aversion. For risk averse farmers, production under CIS increases expected utility relative to non-CIS production. Although the expected utilities converge as farmers become more risk-taking, it is worth noting that even at higher levels of r, that is, at values at which individuals become risk neutral or even risk taking, we find that CIS is associated with an increase in utility. The question, of course, is whether the increase in expected utility is sufficient to offset the costs associated with the program, and we will address this question in the next section.

4.6. Introducing costs for cost–benefit analysis

Thus far, we have focused primarily on the private costs and benefits associated with CIS. From a policy perspective, a government or NGO will be interested in understanding the cost implications of providing CIS services, whether these costs are small enough for the program costs to be smaller than the private benefits accrued to targeted beneficiaries, and whether alternative investments could achieve equal utility gains. To answer these questions, we consider a situation in which the government or a donor would increase the consumption of CIS non-users in order to provide them with equal expected utility as CIS users. This can also be interpreted as the monetary equivalent of the utility gains that CIS users achieve relative to non-users, that is, as the private benefit associated with introducing CIS.

Figure 7 shows the increase in consumption that each of the three groups of CIS non-users would need to achieve equal utility as the three groups of CIS users, or the monetary equivalent of utility gains associated with CIS. To achieve the same level of expected utility in one season, MHH from non-CIS households would require on average an increase in consumption of 1,100 Cedi (93 USD[14]), while the required increase in consumption for women in FHH is 900 CEDI (76 USD), and 780 Cedi (65 USD) for women in MHH. Put differently, investing in CIS would create a utility gain that is equivalent to an increase in consumption of 93 USD for male household heads, 76 USD for women in FHH, and 65 USD for women in MHH. If the total program cost per user is some number X, the benefit–cost ratio can be defined as $76/X$, $64/X$, and $51/X$ for men, women heads and women in MHH, respectively.[15] These benefit–cost ratios can be compared with other types of programs to prioritize investments.

Note that these estimated utility gains are substantially greater than the benefits in terms of increased expected income across respondents. The utility framework allowed us to quantify the gains from increased leisure enjoyed by CIS users. In future work, one could go a step further than presented in the current paper and decompose the difference in utility gains estimated using the two methods into a portion that is related to differences in the intrahousehold distribution of consumption, the introduction of risk preferences, and the introduction of leisure into the framework.

14 We use May, 2023 conversion rates where 1 USD=11.85 Ghanian Cedi.

15 The comparison of CIS users and non-users draws on variation in whether households, are using any CIS, from a range of CIS that are available to them. The goal is to illustrate the use of the framework, not to provide an exact cost–benefit figure for a particular CIS program. We do not have information on the implementation costs of the alternative CIS that are available to farmers in the study population, and therefore leave open the exact cost figure.

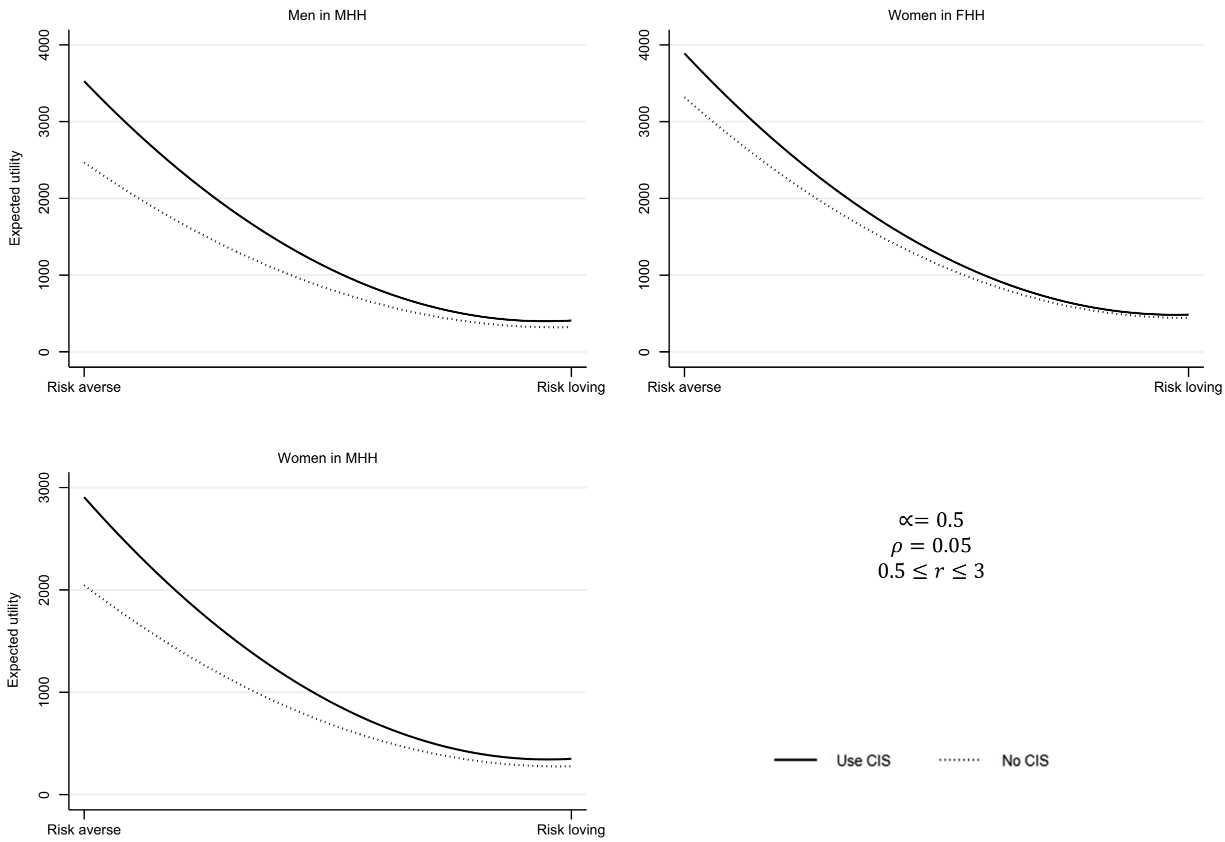


FIGURE 6
Expected utility and degree of risk aversion.

5. Discussion and conclusions

Governments and development agencies have invested millions of dollars in developing agricultural innovations to help farmers cope with climate risks *ex ante*. Understanding the costs and benefits of these innovations helps in justifying, prioritizing, and targeting the right packages to the right groups of farmers. Although previous studies have evaluated the costs and benefits of various innovations to enhance resilience in agriculture, most studies have focused on monetary outcomes at the household level, and typically do not quantify the benefits from gender-related outcomes such as increased women's empowerment and bargaining power from providing women with access to better information, financial services, or production technologies. In addition, given that these studies are conducted at the household level, The findings might also not be generalizable in households where members do not share identical bargaining power and preferences. Finally, existing cost benefit analyses (CBA) typically do not consider the effects that agricultural innovations have on farmers' risk exposure and ability to smooth consumption, which can have utility benefits for risk averse farmers even if the average level of consumption remains the same.

The aim of this study was to illustrate a new framework for the cost–benefit analysis of innovations in agriculture, particularly those aimed to enhance resilience. It contributes to the literature by quantifying a range of costs and benefits that have been previously ignored, while also accounting for how these outcomes are distributed among individuals within the household. To that end, we propose a non-unitary utility framework whereby individuals within the household are assumed to maximize utility from consumption—based on their share of payoffs from agricultural production, and the value of labor that they allocate in the market, determining their payoffs from off-farm activities—as well as leisure. Bargaining weights determine the share of agricultural output that is allocated to each individual within the household. Income realizations and associated decisions are analyzed under three weather outcomes: normal; moderate; and severe. We aggregate across these three weather scenarios by taking an individual's expected utility, using subjective beliefs of the probability at which each weather scenario occurs. We analyze utility gains separately for three groups of farmers: men in male-headed households, women living in male-headed households, and women in female-headed households.

We illustrate our framework for cost–benefit analysis through an empirical application, focusing on baseline information collected in the context of a climate information service (CIS) that is being rolled out in Ghana with support from a World Bank-funded program on Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA). We find that farmers using CIS invest more in their farms, especially under moderate weather conditions, consistent with the idea that resilience technologies promoted through CIS are particularly effective under those types of weather conditions. We also find that CIS use is positively correlated with agricultural incomes, which could be attributed to the high farm investment among users.

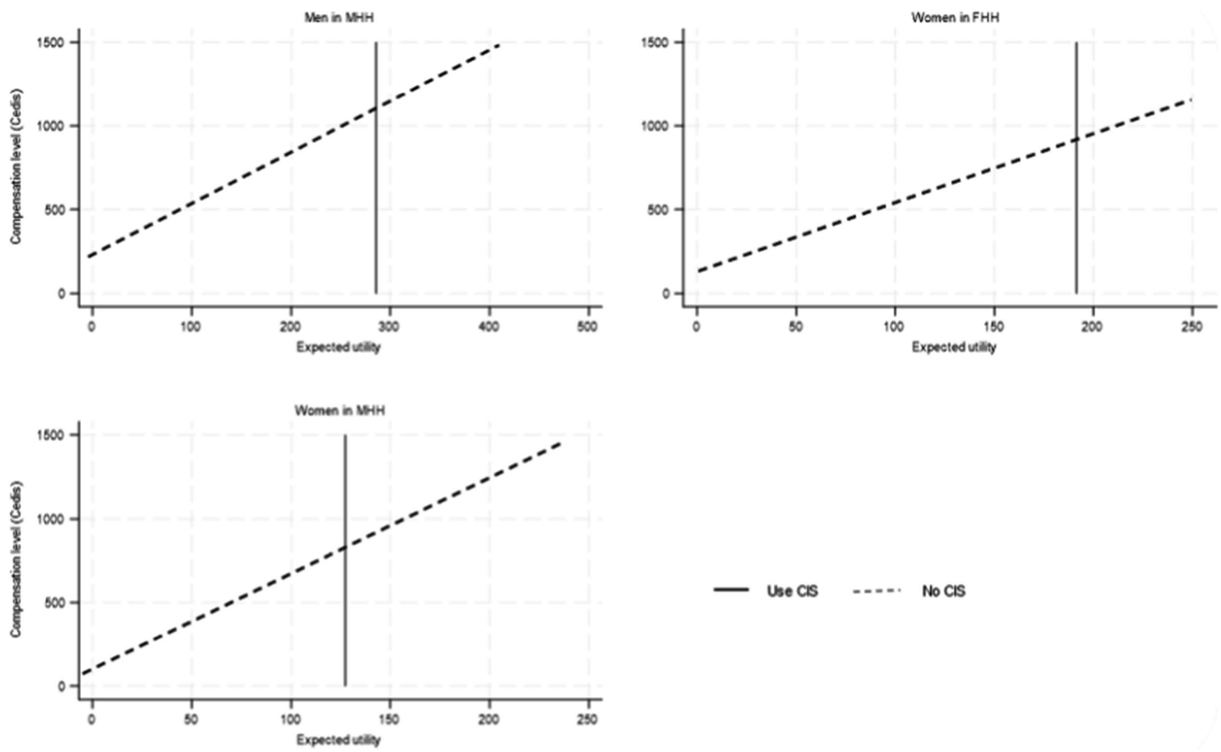


FIGURE 7
Monetary compensation for CIS non-users.

Women living in male-headed households have lower bargaining weights, translating into lower consumption levels.

Combining these outcomes into our expected utility model, we find significant differences in expected utility between users and non-users of CIS. On average, CIS usage is associated with an increase in expected utility of 37 percent, and we find that the monetary equivalent of these utility gains is substantially greater than the benefits one would have derived under more common CBA approaches, which focus on changes in expected income levels and investments alone. Future work will explore in more detail what is driving these differences, and to what extent they are related to the focus on the intrahousehold distribution of benefits associated with CIS use, to integrating changes in leisure in the framework, versus the use of an expected utility framework in which households are assumed to be risk averse.

Moreover, we find that CIS usage is associated with increased utility for all three types of individuals, including men in male-headed households, women in female-headed households, and women in male-headed households; and that this finding is robust to changing the parameter of risk aversion assumed in the expected utility model. However, we find that the greatest utility gains from CIS accrue to household heads; the monetary equivalents of the estimated welfare gains correspond to 93 and 76 USD for male and female household heads respectively, versus a substantially smaller 65 USD for women in male-headed households. These differences in welfare gains are primarily related to the lower bargaining power and higher labor burdens of women, relative to the household heads. CIS usage was not associated with an improvement in these outcomes. If CIS were associated with an increase in bargaining power among women in male-headed households, or with lower labor burdens for this group of women, we would have expected to see greater utility gains.

Our study has a number of limitations. First, the theoretical model ignores time dynamics. It could be that resilience-enhancing innovations have costs in the present that result in long-term benefits, for instance in terms of increased productivity from soil conservation, or simply that there is a learning curve around adopting new technologies and practices, and that it takes time for the benefits associated with this adoption to materialize. For tractability, we abstained from bringing this time dimension into the current framework, but one could easily extend it to also incorporate future periods in the utility framework, along with discounting of future utility terms by using measures of an individual's time preference.

In addition, in the empirical case study, we relied on a comparison of farmers using CIS versus those that have opted not to be using CIS. Any changes in outcomes for CIS users and non-users cannot be interpreted as causal, and the welfare benefits presented in this paper purely serve as an illustration of how the framework could be applied. Ideally, one would estimate gains in consumption and leisure under various weather conditions using more rigorous econometric methods, for instance by leveraging randomized controlled trials (RCTs) or quasi-experimental approaches. Moreover, instead of asking farmers to project their agricultural incomes, farming investments and time allocations under different weather scenarios, longer-term panel data collection could help estimate the effects of alternative weather conditions on these outcomes, which would provide more objective measures of the distribution of consumption and leisure. These limitations will be addressed in future stages of the AICCRA program, as the program is rolling out a set of RCTs in various settings and collecting additional rounds of data.

In conclusion, we find that the use of an expected utility framework can enrich cost–benefit analysis of innovations that have been developed with the aim of enhancing resilience. The framework helps quantify welfare benefits associated with non-monetary outcomes that are nonetheless important from a development perspective, such as improved consumption smoothing, changes in bargaining power, changes in labor allocations and time use, and, for a given set of bargaining weights, consumption levels and labor allocations, the distribution of benefits within a household. We show that it is important for cost–benefit analysis to move beyond quantifying the net present value of expected income gains, and consider a broader range of development objectives, as bringing in non-monetary outcomes can help quantify the outcomes that public sector investments are looking for.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by IFPRI. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AT: questionnaire design, data cleaning, data analysis, and writing. BK: questionnaire design, data analysis, and writing. OD: data collection and writing. All authors contributed to the article and approved the submitted version.

Funding

This work was funded by the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) program, which is supported by a grant from the International Development Association of the World Bank. The authors are grateful to Stellamaris Aju for research assistance, and to Steve Zebiak and Alison Rose from Columbia University for their support and guidance in implementing this work. All errors are our own.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewers MM and SN declared a shared research partnership group (CGIAR) with the authors to the handling editor at the time of review.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aguiar, M., and Hurst, E. (2007). Measuring trends in leisure: the allocation of time over five decades. *Q. J. Econ.* 122, 969–1006. doi: 10.1162/qjec.122.3.969

Alderman, H., and Sahn, D. E. (1993). Substitution between goods and leisure in a developing country. *Am. J. Agric. Econ.* 75, 875–883. doi: 10.2307/1243975

Alkire, S., Meinzen-Dick, R., Peterman, A., Quisumbing, A., Seymour, G., and Vaz, A. (2013). The Women's empowerment in agriculture index. *World Dev.* 52, 71–91. doi: 10.1016/j.worlddev.2013.06.007

Anderson, S., and Eswaran, M. (2009). What determines female autonomy? Evidence from Bangladesh. *J. Dev. Econ.* 90, 179–191. doi: 10.1016/j.jdeveco.2008.10.004

Antwi-Agyei, P., Amanor, K., Hogarh, J. N., and Dougill, A. J. (2021a). Predictors of access to and willingness to pay for climate information services in North-Eastern Ghana: a gendered perspective. *Environ. Dev.* 37:100580. doi: 10.1016/j.envdev.2020.100580

Antwi-Agyei, P., Dougill, A. J., and Abaidoo, R. C. (2021b). Opportunities and barriers for using climate information for building resilient agricultural systems in Sudan savannah agro-ecological zone of North-Eastern Ghana. *Clim. Serv.* 22:100226. doi: 10.1016/j.cliser.2021.100226

Asrar, G., Ryabinin, V., and Detemmerman, V. (2020). Climate science and services: providing climate information for adaptation, sustainable development and risk management. *Curr. Opin. Environ. Sustain.* 4, 88–100. doi: 10.1016/j.cosust.2012.01.003

Attanasio, O. (2009). Expectations and perceptions in developing countries: their measurement and their use. *Am. Econ. Rev.* 99, 87–92. doi: 10.1257/aer.99.2.87

Balaji, V., and Craufurd, P. (2011). *Using information and communication technologies to disseminate and exchange agriculture-related climate information in the indo Gangetic Plains*. Copenhagen, Denmark: CCAFS.

Balmford, A., Fisher, B., Green, R. E., Naidoo, R., Strassburg, B., Turner, R. K., et al. (2011). Bringing ecosystem services into the real world: an operational framework for assessing the economic conse-quences of losing wild nature. *Environ. Resour. Econ.* 48, 161–175. doi: 10.1007/s10640-010-9413-2

Beatty, J., and Torbert, W. (2003). The false duality of work and leisure. *J. Manag. Inq.* 12, 239–252. doi: 10.1177/1056492603256340

Beuchelt, T. D., and Badstue, L. (2013). Gender, nutrition-and climate-smart food production: opportunities and trade-offs. *Food Security* 5, 709–721. doi: 10.1007/s12571-013-0290-8

Beuchelt, T. D. (2016). Gender, social equity and innovations in smallholder farming systems: Pitfalls and pathways. *In Technological and institutional innovations for marginalized smallholders in agricultural development*, 181–198.

Binswanger, H. (1980). Attitudes toward risk: experimental measurement in rural India. *Am. J. Agric. Econ.* 62, 395–407. doi: 10.2307/1240194

Blumberg, R. L., and Coleman, M. T. (1989). A theoretical look at the gender balance of power in the American couple. *J. Fam. Issues* 10, 225–250. doi: 10.1177/019251389010002005

Browning, C. R., Gardner, M., Maimon, D., and Brooks-Gunn, J. (2014). Collective efficacy and the contingent consequences of exposure to life-threatening violence. *Dev. Psychol.* 50, 1878–1890. doi: 10.1037/a0036767

CARE-Burundi (2020). *Costs and Benefits of Applying a Gender-Transformative Approach in Agriculture programming*. Evaluation of the EKATA Model in Burundi. Available at: https://www.careevaluations.org/wp-content/uploads/Win-Win-Final-Cost-Benefit-Analysis.pdf.

Chiappori, P. A. (1988). Rational household labor supply. *Econometrica* 56, 63–90. doi: 10.2307/1911842

Chiappori, P. A. (1992). Collective labor supply and welfare. *J. Polit. Econ.* 100, 437–467. doi: 10.1086/261825

Clarke, D., and Vargas Hill, R. (2013). "Cost-benefit analysis of the African risk capacity facility." IFPRI Discussion Paper 01292.

Choi, K. J., Shim, G., and Shin, Y. H. (2008). Optimal portfolio, consumption-leisure and retirement choice problem with CES utility. *Math. Financ.* 18, 445–472. doi: 10.1111/j.1467-9965.2008.00341.x

Damba, O. T., Kizito, F., Bonilla-Findji, O., Yeboah, S., Oppong-Mensah, B., Clottey, V., et al. (2021). Climate Smart Agriculture (CSA) -Climate Information Services (CIS) Prioritization in Ghana: Smartness Assessments and Outcomes. *Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) Technical Report.*

Demetriades, J., and Esplen, E. (2010). The gender dimensions of poverty and climate change adaptation. *Social Dimensions of Climate Change*. 133.

Dinh, D. T. (2020) Economic valuation of agricultural producers' WTP for the weather information service – A case study in Central Vietnam. E3S web of conferences 203, 03016 (2020)

Diouf, N. S., Ouedraogo, I., Zougmoré, R., Ouedraogo, M., Partey, S., and Gumucio, T. (2019). Factors influencing gendered access to climate information services for farming in Senegal. *Gend. Technol. Dev.* 23, 93–110. doi: 10.1080/09718524.2019.1649790

Donni, O., and Chiappori, P. A. (2011). "Nonunitary models of household behavior: a survey of the literature" in *Household economic behaviors. International series on consumer science*. ed. J. Molina (New York, NY: Springer)

Doss, C. (2013). Intrahousehold bargaining and resource allocation in developing countries. *World Bank Res. Obs.* 28, 52–78. doi: 10.1093/wbro/lkt001

Eckel, C., and Grossman, P. (2002). Sex differences and statistical stereotyping in attitudes toward financial risk. *Evol. Hum. Behav.* 23, 281–295. doi: 10.1016/S1090-5138(02)00097-1

Fafchamps, M. (2005). *Intrahousehold Welfare* Oxford. Oxford University Press.

Falk, A., Becker, A., Dohmen, T., Enke, B., and Huffman, D. (2018). Global evidence on economic preferences. *Q. J. Econ.* 133, 1645–1692. doi: 10.1093/qje/qjy013

FAO (Food and Agriculture Organization of the United Nations). (2010). *Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation*, Rome, FAO

FAO and World Bank. (2018). *Food data collection in household consumption and expenditure surveys: guidelines for low-and middle-income countries* Rome: FAO; World Bank.

Friedberg, L., and Webb, A. (2006). Determinants and consequences of bargaining power in households. Center for retirement research at Boston University. Working paper, 2006–13.

Friedman-Sanchez, G. (2006). Assets in intra-household of bargaining among cut-flower workers in Colombia. *Fem. Econ.* 12, 247–269. doi: 10.1080/13545700500508551

Fuglie, K. (2016). The growing role of the private sector in agricultural research and development world-wide. *Glob. Food Sec.* 10, 29–38. doi: 10.1016/j.gfs.2016.07.005

Fuglie, K., Madhur, G., Aparajita, G., and William, F. (2020). *Harvesting prosperity: Technology and productivity growth in agriculture*. Washington, DC: World Bank.

Georgeson, L., Maslin, M., and Poessinouw, M. (2017). Global disparity in the supply of commercial weather and climate information services. *Sci. Adv.* 24:1602632. doi: 10.1126/sciadv.1602632

Gitonga, Z. M., Visser, M., and Mulwa, C. (2020). Can climate information salvage livelihoods in arid and semiarid lands? An evaluation of access, use and impact in Namibia. *World Dev. Perspect.* 20:100239. doi: 10.1016/j.wdp.2020.100239

Guido, Z., Knudson, C., Campbell, D., and Tomlinson, J. (2020). Climate information services for adaptation: what does it mean to know the context? *Clim. Dev.* 12, 395–407. doi: 10.1080/17565529.2019.1630352

Gumucio, T., Hansen, J., Huyer, S., and van Huysen, T. (2020). Gender-responsive rural climate services: a review of the literature. *Clim. Dev.* 12, 241–254. doi: 10.1080/17565529.2019.1613216

Haddad, L., Hoddinott, J., and Alderman, H. (1998). Intrahousehold resource allocation in developing countries: models, methods, and policies. *Food Nutr. Bull.* 19, 71–72. doi: 10.1177/156482659801900111

Hansen, J., Mason, S., Sun, L., and Tall, A. (2011). Review of seasonal climate forecasting for agriculture in sub-Saharan Africa. *Exp. Agric.* 47, 205–240. doi: 10.1017/S0014479710000876

Howe, L. D., Hargreaves, J. R., Gabrysch, S., and Huttly, S. R. A. (2009). Is the wealth index a proxy for consumption expenditure? A systematic review. *J. Epidemiol. Community Health* 2009, 871–877. doi: 10.1136/jech.2009.088021

Huyer, S., Hansen, J., Rose, A., Vaughan, C., and Huysen, T (2017) What we know about gender and rural climate services. CCAFS info note in agriculture programming: Evaluation of the EKATA model in Burundi

Jappelli, T., and Pistaferri, L. (2000). Using subjective income expectations to test for excess sensitivity of consumption to predicted income growth. *Eur. Econ. Rev.* 44, 337–358. doi: 10.1016/S0014-2921(98)00069-5

Jensen, N., Barrett, C., and Mude, A. (2017). Cash transfers and index insurance: a comparative impact analysis from northern Kenya. *J. Dev. Econ.* 129, 14–28. doi: 10.1016/j.jdeveco.2017.08.002

Kabeer, N. (1992). Evaluating cost-benefit analysis as a tool for gender planning. *Dev. Chang.* 23, 115–139. doi: 10.1111/j.1467-7660.1992.tb00448.x

Kachelmeier, J., and Shehata, M. (1992). Examining risk preferences under high monetary incentives: experimental evidence from the People's republic of China. *Am. Econ. Rev.* 82, 1120–1141.

Kramer, B., and Ceballos, F. (2018). *Enhancing adaptive capacity through climate-smart insurance: Theory and evidence from India. 30th International Conference of Agricultural Economists.* Vancouver, Canada.

Kramer, B., Rusconi, R., and Glauber, J. (2020). Five years of regional risk pooling an updated cost-benefit analysis of the African risk capacity. IFPRI discussion paper 01965

Lele, U., and Goswami, S. (2021). Financing for sustainable structural transformation, food for all: International organizations and the transformation of agriculture. Oxford, 2021; online edn, Oxford Academic, 18 Nov. 2021.

Lim, B. H., and Lee, H. S. (2021). Household utility maximization with life insurance: a CES utility case. *Japan J. Indust. Appl. Math.* 38, 271–295. doi: 10.1007/s13160-020-00437-9

Lybbert, T. J., and Sumner, D. A. (2012). Agricultural technologies for climate change in developing countries: policy options for innovation and technology diffusion. *Food Policy* 37, 114–123. doi: 10.1016/j.foodpol.2011.11.001

Mahul, O., and Stutley, C. (2010). *Government support to agricultural insurance challenges and options for developing countries*. Washington, DC: The World Bank

Manser, M., and Brown, M. (1980). Marriage and household decision-making: a bargaining analysis. *Int. Econ. Rev.* 21, 31–44. doi: 10.2307/2526238

Marta-Pedroso, C., Domingos, T., Freitas, H., and de Groot, R. (2007). Cost–benefit analysis of the zonal program of Castro Verde (Portugal): highlighting the trade-off between biodiversity and soil conservation. *Soil Tillage Res.* 97, 79–90. doi: 10.1016/j.still.2007.08.010

McElroy, M., and Hornery, M. (1981). Nash-bargained household decisions: toward a generalization. *Int. Econ. Rev.* 22, 333–349. doi: 10.2307/2526280

McKune, S., Poulsen, L., Russo, S., Devereux, T., Faas, S., McOmber, C., et al. (2018). Reaching the end goal: do interventions to improve climate information services lead to greater food security? *Clim. Risk Manag.* 22, 22–41. doi: 10.1016/j.crm.2018.08.002

Mutenje, M. J., Farnworth, C. R., Stirling, C., Thierfelder, C., Mupangwa, W., and Nyagumbo, I. (2019). A cost-benefit analysis of climate-smart agriculture options in southern Africa: balancing gender and technology. *Ecol. Econ.* 163, 126–137. doi: 10.1016/j.ecolecon.2019.05.013

Naab, F., Abubakari, Z., and Ahmed, A. (2019). The role of climate services in agricultural productivity in Ghana: the perspectives of farmers and institutions. *Clim. Serv.* 13, 24–32. doi: 10.1016/j.cliser.2019.01.007

Nganga, S.K., Miller, V., Essegbey, G.O., Naaminong, K., Ansah, V., Nutsukpo, D., et al. (2017a). *Cost and benefit analysis for climate-smart agricultural (CSA) practices in the coastal Savannah agro-ecological zone (AEZ) of Ghana*. Uganda: Sub-Regional Office.

Nganga, S.K., Notenbaert, A., Mwungu, C.M., Mwongera, C., and Girvetz, E. (2017b). *Cost and benefit analysis for climate-smart soil practices in Western Kenya*, Kenya: Subregional Office for Africa.

Nidumolu, U., Lim-Camacho, L., Gaillard, E., Hayman, P., and Howden, M. (2020). Linking climate forecasts to rural livelihoods: mapping decisions, information networks and value chains. *Weather Clim. Extrem.* 27:100174. doi: 10.1016/j.wace.2018.06.001

OECD (2015). *Disaster risk financing a global survey of practices and challenges*. Berlin: OECD.

Ouédraogo, M., Barry, S., Zougmoré, R. B., Partey, S. T., Somé, L., and Baki, G. (2018). Farmers' willingness to pay for climate information services: evidence from cowpea and sesame producers in northern Burkina Faso. *Sustainability.* 10:3. doi: 10.3390/su10030611

Rupert, P., Rogerson, R., and Wright, R. (1995). Estimating substitution elasticities in household production models. *Economic Theory* 6, 179–193.

Sain, G., Ana María, A., Corner-Dolloff, C., Miguel, L., Andreea, L., Martínez-Baron, D., et al. (2017). Costs and benefits of climate-smart agriculture: the case of the dry corridor in Guatemala. *Agric. Syst.* 151, 163–173. doi: 10.1016/j.agsy.2016.05.004

Sen, A. (1984), *Resources, values and development* (Oxford: Clarendon Press).

Skinner, J. (1987). A superior measure of consumption from the panel study of income dynamics. *Econ. Lett.* 23, 213–216. doi: 10.1016/0165-1765(87)90042-5

Smith, H. E., Sallu, S. M., Whitfield, S., Gaworek-Michalczenia, M. F., Recha, J. W., Sayula, G. J., et al. (2021). Innovation systems and affordances in climate smart agriculture. *J. Rural. Stud.* 87, 199–212. doi: 10.1016/j.jrurstud.2021.09.001

Smith, L., and Walker, M. (1993). Rewards, experience, and decision costs in first price auctions. *Econ. Inq.* 31, 237–244. doi: 10.1111/j.1465-7295.1993.tb00880.x

Sweeney, S., Vassall, A., Foster, N., Simms, V., Ilboudo, P., Kimaro, G., et al. (2016). Methodological issues to consider when collecting data to estimate poverty impact in economic evaluations in low-income and middle-income countries. *Health Econ.* 25, 42–52. doi: 10.1002/hec.3304

Tall, A., Kristjanson, P.M., Chaudhury, M., McKune, S., and Zougmoré, R.B. (2014). Who gets the information? Gender, power and equity considerations in the design of climate services for farmers. CCAFS Working Paper Research Program on Climate Change, Agriculture and Food Security (CCAFS) Copenhagen, Denmark: CGIAR.

Tanner, T., and Mitchell, T. (2008). *Entrenchment or Enhancement: Could Climate Change Adaptation Help Reduce Chronic Poverty?, Working Paper 106*, Manchester: Chronic Poverty Research Centre.

Thornton, P. K., Ericksen, P. J., Herrero, M., and Challinor, A. J. (2014). Climate variability and vulnerability to climate change: a review. *Glob Chang Biol.* 20, 3313–3328. doi: 10.1111/gcb.12581

USAID (2013). *Climate services. Better information for climate-resilient decision making*. Washington: USAID

Vaughan, C., Muth, M. F., and Brown, D. P. (2019). Evaluation of regional climate services: learning from seasonal-scale examples across the Americas. *Clim. Serv.* 15:100104. doi: 10.1016/j.cliser.2019.100104

Wafula, J., Karimjee, Y., Tamba, Y., Malava, G., Muchiri, C., Koech, G., et al. (2018). Probabilistic assessment of investment options in honey value chains in Lamu county, Kenya. *Front. Appl. Math. Stat.* 4:2018. doi: 10.3389/fams.2018.00006

Walker, J. (2013). Time poverty, gender and well-being: lessons from the Kyrgyz Swiss Swedish health Programme. *Dev. Pract.* 23, 57–68. doi: 10.1080/09614524.2013.751357

Wallemacq, P., and House, R. (2018). Economic losses, poverty & disasters: 1998–2017. United Nations Office for disaster risk reduction (UNDRR) & Centre for Research on the epidemiology of disasters (CRED).

Wei, X., Qu, H., and Ma, E. (2016). How does leisure time affect production efficiency? Evidence from China, Japan, and the US. *Soc. Indic. Res.* 127, 101–122. doi: 10.1007/s11205-015-0962-1

Williams, P. A., Karanja Ng'ang'a, S., Crespo, O., and Abu, M. (2020). Cost and benefit analysis of adopting climate adaptation practices among smallholders: the case of five selected practices in Ghana. *Clim. Serv.* 20:100198. doi: 10.1016/j.cliser.2020.100198

World Bank (2011). *Climate-smart agriculture: A call to action*. Washington, DC: World Bank.

World Meteorological Organization, (2014). *Implementation plan of the global framework for climate services* Geneva: World Meteorological Organization.

Yegbemey, R. N., and Egah, J. (2021). Reaching out to smallholder farmers in developing countries with climate services: a literature review of current information delivery channels. *Clim. Serv.* 23:100253. doi: 10.1016/j.cliser.2021.100253

10.3389/fsufs.2023.1129419

Appendix

Figure A1 illustrates how CIS can benefit the farmer through increased agricultural payoffs. Payoffs depend on CIS use (which we denote by the symbol γ) and weather conditions (φ). The dashed line indicates payoffs for a farmer that is not using the recommendations provided by CIS ($\gamma = 0$), while the solid line indicates payoffs for a farmer that is implementing the recommendations by CIS ($\gamma = 1$). Under normal weather conditions, $\varphi \leq \varphi^0$ payoffs are at their maximum level, and farmers do not need CIS to attain this maximum payoff. When facing moderate weather conditions, $\varphi \in \left(\varphi^0, \varphi^1\right)$, farmers are experiencing reduced payoffs under normal practices, as existing practices and technologies are not sufficient to address the stress imposed on crops and livestock. However, when following the recommendations provided by CIS, a farmer can mitigate some of these losses, and experience the adverse effects of climate risks only once weather conditions become more severe, $\varphi \in \left(\varphi^1, \varphi^2\right)$. In years with extreme weather conditions, $\varphi > \varphi^2$, payoffs tend to zero regardless of whether a farmer is using CIS. We will use this simple model for the relationship between payoffs from agricultural activities, weather conditions, and the adoption of CIS to structure our framework for cost–benefit analysis.

Following Figure A1, we assume that for a given level of labor and agricultural investment, income from agricultural production does not depend on whether a farmer adopts CIS-recommended practices in normal or severe states of nature, but under moderate weather conditions, CIS-recommended practices shield agricultural payoffs from losses. Formally, $Y(\cdot;1,1) = Y(\cdot;0,1) < Y(\cdot;0,2) < Y(\cdot;1,2) < Y(\cdot;1,3) = Y(\cdot;0,3)$.

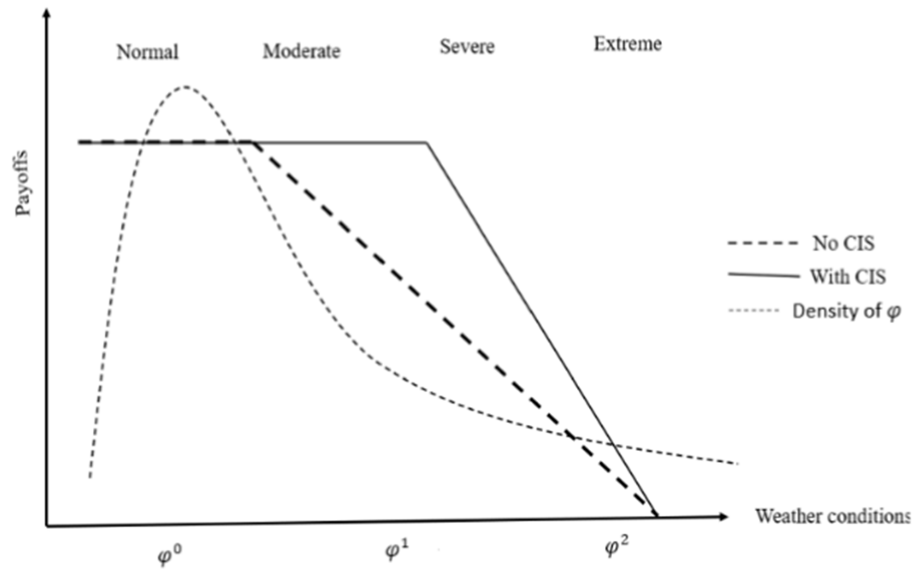


FIGURE A1
Density of Weather shocks and payoffs due to CIS (Adapted from Kramer and Ceballos, 2018).

frontiers | Frontiers in Sustainable Food Systems

TYPE Policy and Practice Reviews
PUBLISHED 14 September 2023
DOI 10.3389/fsufs.2023.1059063

Check for updates

OPEN ACCESS

EDITED BY
Ademola Braimoh,
World Bank Group, United States

REVIEWED BY
Eleanor Milne,
Colorado State University, United States
Sandra Mara de Alencar Schiavi,
State University of Maringá, Brazil

*CORRESPONDENCE
Jonathan Wirths
✉ jonathan.wirths@gmail.com

RECEIVED 30 September 2022
ACCEPTED 21 July 2023
PUBLISHED 14 September 2023

CITATION
Zurek M, Wirths J, Hebinck A, Crawford S, Lidder P, Prasad PVV, Tittonell P, Herrero M and Compton J (2023) Principles for guiding research and innovation toward sustainable and equitable agrifood systems.
Front. Sustain. Food Syst. 7:1059063.
doi: 10.3389/fsufs.2023.1059063

Principles for guiding research and innovation toward sustainable and equitable agrifood systems

Monika Zurek[1], Jonathan Wirths[2,3]*, Aniek Hebinck[4], Scarlett Crawford[5], Preetmoninder Lidder[2], P. V. Vara Prasad[6], Pablo Tittonell[7,8,9], Mario Herrero[10] and Julia Compton[11,12] on behalf of Taskforce

[1]Food System Transformation Group, ECI, University of Oxford, Oxford, United Kingdom, [2]Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, [3]Food and Agriculture Organization, Bonn, Germany, [4]Dutch Research Institute for Transitions, Erasmus University Rotterdam, Rotterdam, Netherlands, [5]CGIAR, Systems Office, Montpellier, France, [6]Feed the Future Sustainable Intensification Innovation Lab, Kansas State University, Manhattan, KS, United States, [7]Instituto de Investigaciones Forestales y Agropecuarias de Bariloche (IFAB), INTA-CONICET, San Carlos de Bariloche, Argentina, [8]CIRAD, Montpellier, France, [9]Groningen Institute of Evolutionary Life Sciences, University of Groningen, Groningen, Netherlands, [10]Department of Global Development, College of Agriculture and Life Sciences, and Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY, United States, [11]Independent Consultant, Cardiff, United Kingdom, [12]Commission for Sustainable Agriculture Intensification, International Water Management Institute, Colombo, Sri Lanka

Investments in research and innovation are critical for transformations toward sustainable agrifood systems and for meeting the Sustainable Development Goals and the Paris Climate Agreement. However, the frequent neglect of environmental and social goals by investors remains a major challenge. System-oriented approaches to designing and monitoring innovations can be a promising solution to guide innovations and allow investors to identify those that are more sustainable. This article presents a set of eight 'Principles for Agrifood Research and Innovation' developed by an international multi-stakeholder task force including staff of research agencies, funders and impact investors, private sector, non-governmental organizations, and benchmarking organizations. The article explains the rationale for the selection of the principles and describes potential ways forward for their uptake and implementation, building on pilots done by several research and funding organizations.

KEYWORDS

principles for research, principles for innovation, sustainable food systems, agrifood systems, sustainable agriculture, social equity, ethical, environmental sustainability

1. Introduction

Today's agrifood systems require urgent transformation to better provide food and nutrition security to global consumers while minimizing their negative environmental and social impacts (Zurek et al., 2022a). Agrifood systems "encompass the entire range of actors, and their interlinked value-adding activities, engaged in the primary production of food and non-food agricultural products, as well as in storage, aggregation, post-harvest handling, transportation, processing, distribution, marketing, disposal and consumption of all food products including those of non-agricultural origin" (FAO, 2022).[1] Innovation constitutes a critical component for

1 The definitions of *food* systems and *agrifood* systems differ in that the latter explicitly also includes the production of agricultural non-food products.

initiating and sustaining transformations of agrifood systems (Herrero et al., 2020; International Energy Agency, 2022) and in relation to agrifood systems, "innovation is the process 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, 2022).[2] In the context of this work, innovation includes research that aligns with this definition.

A recent review of the 'innovation investment landscape' in agrifood systems found that less than 7 % of innovation funding for agrifood systems had explicit environmental objectives and less than 4.5 per cent also contained explicit social objectives (Prasad et al., 2023). Contributions of agrifood research and innovation have often been siloed, prioritizing production processes and food security while failing to adequately consider interconnected outcomes (den Boer et al., 2021). Future innovations must therefore begin to consider the whole agrifood system, including environmental and social outcomes, in order to contribute to a transformation toward *sustainable* agrifood systems (SAFS) (Herrero et al., 2020). SAFS are agrifood systems that contribute to food and nutrition security, economic opportunities, and secure livelihood opportunities for agrifood system actors while contributing to the sustainable management and utilization of natural resources as well as social equity (adapted from Sage, 2018). In other words, innovation must consider more complex causal mechanisms that address trade-offs, emerging system properties, and dynamic feedback mechanisms (Foran et al., 2014; den Boer et al., 2021). However, in practice undertaking this is difficult. It is challenging for actors to reliably steer an innovation toward promoting SAFS and understand whether it is worth investing the required time, financial and other resources (Zurek et al., 2021), meaning the lack of guidance here is a major shortcoming.

To address this shortcoming and the related neglect of environmental and social objectives, a diverse task force of experts in agrifood innovation from academia, international organizations, farmers organizations, and the private sector developed actionable principles for guiding innovation toward contributions to SAFS. The aim of the task force was to support research and innovation actors, including investors, managers, implementers, and benchmarking actors, in planning, implementing, and monitoring progress against SAFS objectives. The principles are underpinned by a scoring system that allows users to monitor their progress in realizing the goals set out.

This article elucidates the work of the task force, the principles, and the associated scoring system. It starts with a review of the key challenges for transformative innovations in agrifood systems. Following this, the participatory approach taken in developing the principles is described and the task force's conceptual perspectives on agrifood systems, agrifood innovation, and related principles is outlined. Subsequently, the article presents the eight developed principles and the scoring system supporting their operationalization. It concludes with a set of recommendations for further work in this area and a short discussion on some of the limitations of the principles.

2. Challenges for transformative innovations in agrifood systems

The diverse actors within agrifood systems are interested in varying combinations of outcomes. However, current agrifood systems fall short in both providing adequate food and nutrition security and an equitable distribution of food, resulting in simultaneous malnutrition, hunger, and overconsumption (the 'triple burden of malnutrition') (Holt-Gimenez and Patel, 2012; FAO, IFAD, UNICEF, WFP, WHO, 2021). Concurrently, agrifood systems have a huge environmental footprint, being affected by and driving climate change (Vermeulen et al., 2012b; Mbow et al., 2019), biodiversity loss (Frison et al., 2011; Daskalova et al., 2020), land use change, water use and pollution, and soil degradation (Campbell et al., 2017; OECD, 2019). In addition, they fail to provide equal economic opportunities to food system actors or social equity at large (Mannar et al., 2020; Downs and Fox, 2021; Hebinck et al., 2021; Jacobi et al., 2021). At the household level, they support the livelihoods of 3.83 billion people – many of whom suffer from hunger and poverty (UN DESA, 2021; Davis et al., 2023). These simultaneous demands urgently necessitate a drastic transformation (Béné et al., 2019; Webb et al., 2020). They require new tools, concepts, and management options for change, that is, they require innovations. Currently, there are two major challenges in developing innovations and innovation systems that address sustainability and equity challenges in agrifood systems while safeguarding productivity gains.

The first challenge relates to difficulties in designing innovations for complex systems and knowing whether they are likely to contribute to intended objectives in the long-term (Klerkx and Begemann, 2020; Klerkx and Rose, 2020; Zurek et al., 2021). This complexity is recognized by the growing body of research that builds on agrifood systems thinking – a central springboard for addressing persistent, interdependent challenges. Agrifood systems thinking is an approach for visualizing and analyzing the interconnected nature and dynamics of agrifood system activities and actors, as well as the outcomes and drivers of these activities. Tools, such as visual frameworks, guide users in establishing foundations and finding entry points for new insights and ideas for better system governance (see Section 4 of this paper) (Ericksen, 2008; Ingram and Zurek, 2018; van Berkum et al., 2018).

Understanding systemic interactions in today's complex agrifood systems is key for governance toward sustainability (Brouwer et al., 2020). For example, innovations for nutritional outcomes may also have environmental, economic, or social implications. Here it becomes evident that innovations must consider the interdependence of different activities and how they interact with and impact different system goals and emerging system properties through dynamic feedback mechanisms (Foran et al., 2014). However, predicting and managing the long-term effects of innovations in line with this understanding is a challenge (Zurek et al., 2022b) that complicates planning and assessment, accentuating questions about trade-offs and unintended consequences.

2 Types of innovation include technological, social, policy, institutional and financial innovations, as well as adaptation of longstanding (e.g., indigenous) methods to larger-scale applications, as with some sustainable agricultural approaches (e.g., agroecology) (FAO, 2022).

The second challenge is that the majority of current investments in agrifood systems do not explicitly target social or environmental objectives (nor a combination of the two) (Prasad et al., 2023). They instead prioritize production and food security (den Boer et al., 2021). Additionally, the agrifood 'research and publications landscape' shows that there are massive research gaps in relation to social equity and inclusion outcomes (Hebinck et al., 2021), including those for health and nutrition, women and elderly people, and indigenous and youth populations (Porciello et al., 2021). These research gaps have implications for innovation processes and contribute to de-prioritization of these issues among other reasons. Conventionally, people who invest in or guide innovation processes follow linear and siloed approaches with few targeted outcomes (den Boer et al., 2021). However, because of the interdependent nature of agrifood systems, innovations designed in this way carry the risk of maintaining or exacerbating adverse non-targeted outcomes (Zurek et al., 2021). Seeing the current investment landscape, it is clear that these trade-offs are more likely to occur in social or environmental areas. The goal therefore is to embed the diversity of outcomes and actors in public and private investment decisions so that investors can identify the potential sustainability of an innovation (FAO, 2020; den Boer et al., 2021).

Recognizing and addressing these two challenges is critical for developing and deploying transformative innovations in agrifood systems. This article describes the development of a set of principles that guides innovation toward enabling SAFS. Principles that follow sustainability goals are a promising tool to guide innovation options in this direction (Leach et al., 2012; Herrero et al., 2020; Mottet et al., 2020; de Boon et al., 2022). They enable innovators to contribute to the transformation of agrifood systems more systematically and intentionally while increasing synergies and properly considering trade-offs along the way. The presented principles apply agrifood systems thinking to steer both investments, and the design and implementation of innovations, toward integrating environmental and social objectives, alongside conventional economic and productivity considerations.

3. The task force and methods used

In October 2021, the Commission on Sustainable Agriculture Intensification (CoSAI)[3] established a voluntary international Task Force on Principles and Metrics for Innovation in Sustainable Agrifood Systems (the Taskforce). Guided by CoSAI, over one year, the Taskforce worked on developing a set of principles for operationally guiding and monitoring innovation from an agrifood systems perspective in order to contribute to equity and sustainability objectives. The Taskforce was supported by an Expert Team who organized and summarized meetings, conducted background research, wrote proposals for the principles, and addressed disagreements and ambiguities. The principles were subsequently named 'Principles for Agrifood Research and Innovation'(PARI).

3 The Commission on Sustainable Agriculture Intensification (CoSAI) was a two-year international independent Commission supported by the CGIAR (CoSAI Secretariat, 2022).

3.1. Task force composition

Designing PARI required the Taskforce to incorporate diverse expertise in designing, implementing, or financing research and innovation for agrifood systems. Thus, Taskforce member selection was based on proven knowledge and practical experience in those contexts. However, Taskforce members were invited in their 'individual capacity' (rather than on behalf of their affiliated institution) to provide a level of freedom of expression. Ensuring diverse representation was also a critical requirement because the individual backgrounds of experts strongly influence both the outputs and the later uptake and support by the broader public (Knol et al., 2010). As a result, Taskforce member selection aimed to maximize diversity in stakeholder groups (i.e., research, private sector, civil society, etc.), gender, geographical region, and country-income classification (Zurek et al., 2022b). The balance between private sector and civil society organizations was carefully considered in recognition of their mutually dependent roles in agrifood innovation; Private sector actors carry economic power necessary to establish new industry standards in practice, while civil society organizations are crucial for legitimizing standards through their influence on public opinions about social and environmental challenges (Lambin and Thorlakson, 2018).

Despite a consistent effort to increase diversity during the selection process, representation across the Taskforce's 30 members was not equal. Variety was limited by structural inequalities in the agrifood sector, the necessary expertise criterion, and individual availability. This imbalance was partially mitigated through an additional public consultation. Membership included research organizations (40%), development partners (23%), non-governmental organizations (10%), and UN agencies, farmer organizations, private sector/private investor organizations, and private sector benchmarking organizations (7% each). The gender profile was similarly skewed with 70% of the group identifying as male. Regional representation was led by Europe and Central Asia (30%), followed by Latin America and the Caribbean (20%), North America (17%), South Asia and Sub-Saharan Africa (both 13%), and East Asia and Pacific (7%). The Middle East and North African region were not represented. Most participants (53%) originated from high-income countries, followed by lower- and upper-middle-income countries (both 23%) and one expert (3%) originating from a low-income country (Zurek et al., 2022b). See Annex 1 for a complete list of Taskforce members and categories of representation.

3.2. Methods used and process

For developing PARI, the Expert Team coordinated a participatory process with the 30 Taskforce members over seven 90-120-min meetings. To facilitate participation across disperse geographies, meetings were virtual. They followed the form of 'consensus development panels' (i.e., organized expert meetings), a method that is frequently used as a tool for developing guidelines such as policies and decision protocols in various sectors (Waggoner et al., 2016). However, the Expert Team chose to exceed the typical group size for this method (5–10) to ensure input from various agrifood sector stakeholder groups and to diversify

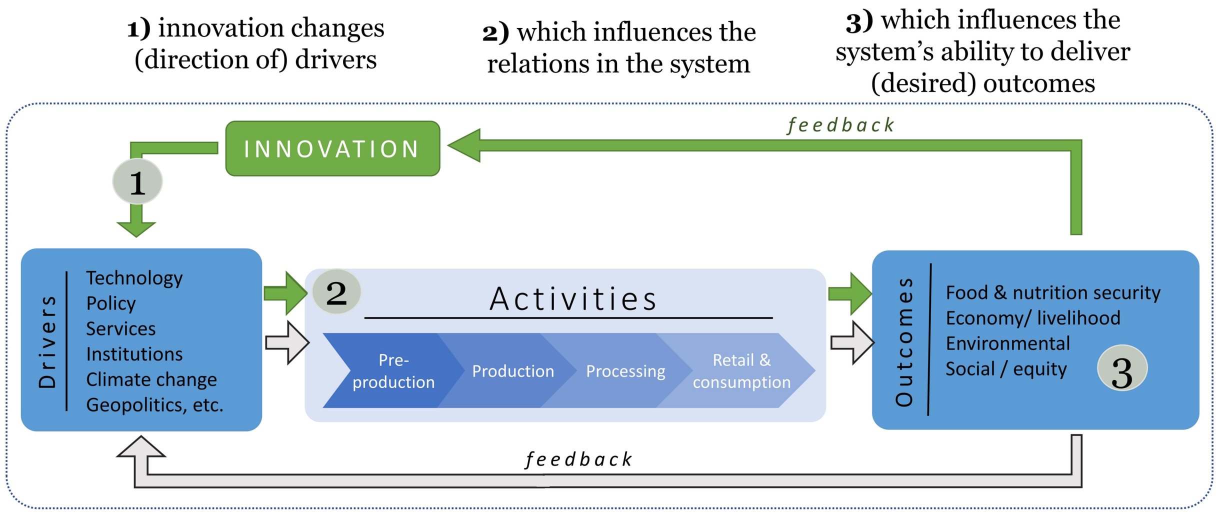


FIGURE 1
Process for developing the Principles for Agrifood Research and Innovation.

representation (Zurek et al., 2022b). Capitalizing on one of the strengths of consensus development panels, the larger group size also granted increased legitimacy to PARI and encouraged advocacy and ownership from within the sector (Waggoner et al., 2016).

During meetings, all decisions were made in plenary. Consensus was reached when a majority of participants actively agreed or had no objection to the inclusion or removal of aspects from the principles or guidance materials. Disagreements or raised concerns were evaluated by the Expert Team and were either resolved immediately or included in the agenda of the next group discussion. Given the larger group size and to mitigate risks of overly vocal Taskforce members (Waggoner et al., 2016), the Expert Team preemptively split the panel into smaller break-out groups of 4–7 experts for important discussion topics. Furthermore, the Expert Team encouraged Taskforce members to raise additional comments between meetings.

Overall, PARI was developed over four phases spanning 1.5 years: *(1) Ideation, research, strategy; (2) development of principles; (3) development of scoring framework and role of metrics; (4) piloting* (see Figure 1).

During the first and second phases, the Expert Team reviewed (grey) literature on innovation principles as well as principles on sustainable agriculture (see Annex 2). It then worked with the Taskforce to prepare a draft set of principles for innovation in agrifood systems. As part of phase two, a public consultation gathered initial feedback on the first version of PARI. Here, a survey, open for one month, was distributed through professional networks and websites reporting on agricultural innovation. This diversified conceptual inputs and provided opportunities for other stakeholders to contribute. In total, 51 experts contributed (predominantly from international organizations, NGOs, government, and academia). Participants provided feedback comprising the need for definitions and enquiries about the operationalization of PARI, especially regarding measurability and monitorability. This feedback was reviewed by the Taskforce, resulting in an improved version of the principles and the subsequent development of the scoring system as a tool for operationalization.

PARI and its scoring system were piloted in 'real world' external projects before the final Taskforce meeting. Piloting included independent applications of PARI to an innovative project (18 in total, mostly small-scale) and/or usability testing (7 sessions).[4] During usability testing, participants were observed by two members of the Expert Team while familiarizing themselves with the principles and guidance materials, taking first application steps, sharing impressions, and asking questions. Feedback from both formats was collected through direct calls, filled-in scoring frameworks as well as a feedback survey.

During the final meeting in March 2022, the Taskforce agreed on the final set of principles (Zurek et al., 2022b). It also discussed handing over PARI to an appropriate lead organization with a global mandate, that could continue their development and promotion. The successor organization would likely finetune individual principles, develop a pertinent catalog of metrics, disseminate PARI among public and private stakeholders, and support them in integrating the tool in existing reporting and benchmarking processes. While an operational set of metrics could not be developed within the time frame of the Taskforce, their role is reflected in the principles and a limited collection (sorted according to sub-principles) was made available to the public.

A visually polished online version of the guidance materials was developed to improve usability of PARI in their current form and support their promotion. This includes two introductory videos that further increase accessibility and user-friendliness (CoSAI Secretariat, 2023).

4 The 18 projects came from the following stakeholder groups: development partner (3), non-governmental organization (5), private sector (4), research organization (6) and were sourced from the Taskforce network and responses to a public call by CoSAI.

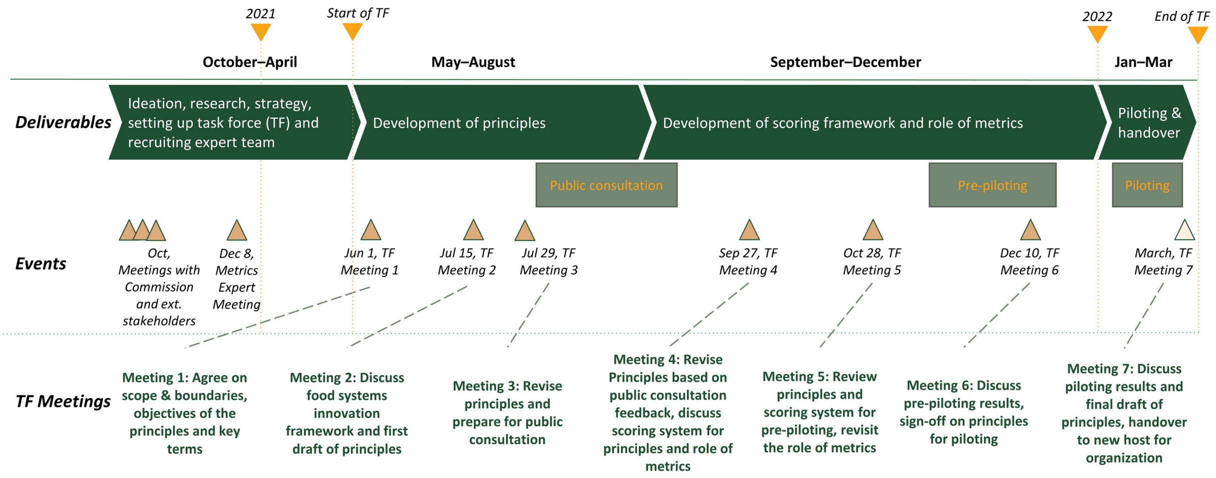


FIGURE 2
Conceptualizing innovation in agrifood systems using three lenses: drivers, activities, and outcomes.

4. Conceptualizing innovation in agrifood systems and related principles

Because "[agri]food systems approaches must be useful to decision makers, and performance can only be improved if decision makers have a better understanding of these underlying interactions and dynamics of food systems change" (Brouwer et al., 2020), it was important that the Taskforce shared a conceptual understanding of innovation's impacts on agrifood systems. To facilitate this, innovation in agrifood systems was considered through a framework comprised of three lenses: drivers, activities, and outcomes of agrifood systems (and their interactions) (see Figure 2). For outcomes to be improved actors must change the driving forces (e.g., institutions and policies, available technologies or cultural habits) that shape how agrifood systems function and which activities are carried out by whom (Ericksen, 2008; Ingram, 2011; van Berkum et al., 2018). Despite the framework simplifying agrifood systems and omitting the feedback loops within innovation processes, it does illustrate how innovation continuously impacts agrifood systems and shows the trajectory of innovation in relation to both its triggers (i.e., desired outcomes) and agrifood system drivers.[5] This provided the Taskforce with a starting point for developing principles that both aligned with innovation's interaction with agrifood systems and had the potential to transform the direction and intensity of the innovation's impact on SAFS outcomes.

The Taskforce's framework was complemented by a complex and non-linear understanding of both agrifood systems (e.g., FAO, 2014, 2018; van Berkum et al., 2018; Zurek et al., 2022c) and innovation (e.g., HLPE, 2019; Koerner and Duda, 2021 based on various frameworks). Viewing agrifood systems from varying angles provides the foundation for developing new insights and ideas for better management practices (Ericksen, 2008; Ingram and Zurek, 2018; van Berkum et al., 2018; Hebinck et al., 2021). These varying angles imply different functionalities for agrifood system actors and have implications for the way they interact with the system. The Taskforce concluded that various agrifood systems perspectives can serve innovations and that the choice depends on the context, including the scale at which an innovation is implemented. Taskforce members utilized this diversity of understandings on agrifood systems and innovation to consider how best to guide innovators and related actors, catering to differing needs.

This perspective on innovation in agrifood systems strengthens the case for a well operationalized set of principles that can continuously and iteratively guide innovation-related actors in balancing intended outcomes and trade-offs at all scales. In the above framework, principles function as both procedural and normative anchors for innovations. They highlight the path to best practice for innovation processes ('the how'), while helping actors align their innovations with their desired outcomes through a systems perspective ('the what'), altering drivers, activities, and the configurations of agrifood system actors.

Various principles on SAFS as well as innovation already exist. CoSAI had however identified a gap in the intersecting area of *innovation principles for SAFS*. To compose such principles, the Taskforce reviewed existing principles based on guidelines and grey literature within the two identified types (see Annex 2). Principles on SAFS usually relate to the goals and outcomes of agrifood systems, e.g., soil health, labor standards, and gender equality. Principles on innovations typically specify procedural steps to support goals and outcomes (e.g., developing a theory of change or undertaking stakeholder consultation) or provide guidance for creating an enabling environment (i.e., innovation systems). For reviewing innovation principles, the Taskforce included principles from various sectors outside of agrifood systems.

5 The Taskforce also used the framework to set their scope of work on pre-production, production and post-harvest activities.

BOX 1: EIGHT PRINCIPLES FOR AGRIFOOD RESEARCH AND INNOVATION (EXCLUDING SUB-PRINCIPLES).

1. Set out a clear theory of change defining intended impacts, based on a food systems perspective and reflexive learning.
2. Design transparent and evidence-based innovation processes.
3. Conduct innovation processes in an inclusive and ethical manner.
4. Address potential trade-offs, synergies, efficiencies, and unintended effects.
5. Consider contribution to improved food and nutrition security and health.
6. Consider contribution to sustainable and circular management and utilization of natural resources.
7. Consider contribution to a viable economy and sustainable livelihoods.
8. Consider contribution to an ethical, equitable, and adaptive agrifood system for current and future generations.

The two types of principles, *in combination*, are required to support innovation in contributing to SAFS (Zurek et al., 2022b). In isolation, each type has limitations. Outcome principles are useful for defining and pursuing objectives but cannot be measured at the beginning of innovation processes. Here, it may only be possible to track intentions and the quality and depth of the processes used to develop the innovation. As a counterpart, process principles provide methodological guidance in the form of best practices for developing innovations. These help steer the development of innovations, though do not specify outcomes. Those innovation principles that facilitate innovation by promoting an enabling environment target conditions that are not necessarily directly influenced by innovators, nor do they account for investor demands around innovation's procedures and progress against outcomes. Hence, a combination of principles on SAFS and innovation process is required for effectively guiding agrifood system actors throughout all stages of the innovation process. In developing first iterations of the principles, the Taskforce reviewed 30 and 28 sets of SAFS and innovation process principles (e.g., the High-Level Panel of Experts' report *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition* (HLPE, 2019) (for outcome principles), and the COP26 (2021) *Transforming Agricultural Innovation Campaign Steering Group's Principles for Transforming Innovation* (2020) or the *World Wildlife Fund's ESG Integration Indicators* (WWF, 2021) (for process principles)).

Three target groups that could use innovation principles for SAFS were identified to help guide the development of PARI. Identifying these target groups allowed the Taskforce to consider how the principles would be used by different groups, how appropriate they would be for each group's needs, and where potential gaps lay in terms of servicing their needs and uses.

- Public and private direct investors in innovation in agrifood systems who need to ensure that their funds are appropriately used to support their SAFS goals (e.g., Bayer CropScience, FAO, USAID).
- Managers and implementers of research for development and innovation, both public and private, who need to plan their work and track progress against SAFS objectives (e.g., CGIAR, Syngenta).
- Certification, benchmarking, and watchdog organizations promoting investment in innovation for environmentally sustainable and socially positive outcomes (e.g., Verra, World Benchmarking Alliance).

5. Actionable principles for research and innovation in sustainable agrifood systems

The Taskforce composed a set of eight principles (i.e., PARI) for guiding innovation projects in targeting sustainable and equitable agrifood system outcomes (see Box 1).

The first four principles focus on best practice *processes* for managing innovative projects. The last four principles focus on *outcomes* of innovation. Each principle is delineated through subprinciples that further guide implementation.[6] Despite being numbered, all principles are of equal importance and their interlinked nature means addressing one can affect others. While the principles are normative, that is, they require users to consider elements of their innovation processes and outcomes, they never stipulate specifics (e.g., modes of production such as agroecological production). The following section presents PARI and the literature underpinning their scientific relevance in guiding agrifood systems' innovation processes. In addition, prominent aspects of discussions within the Taskforce are included. Note that the version of PARI here is a work-in-progress, likely to undergo further changes in the future.

Principle 1: Set out a clear theory of change defining intended impacts, based on a food systems perspective and reflexive learning.
1.1. Clear and flexible theory of change defining intended impact of proposed innovation.
1.2. Applied systems thinking at different scales, including all impacted actors and activities.
1.3. Reflexive monitoring and evaluation to adapt route to impact to changing conditions.

Agrifood innovations are developed in diverse systemic contexts that include a variety of outcomes, objectives, targeted populations, and mechanisms for change. Thus, it is important to specify an innovation's rationale, direction, and mechanism of change from the outset (Hekkert et al., 2020; Klerkx and Begemann, 2020; Mazzucato et al., 2020). Here, constructing a clear theory of change that defines impact pathways and is responsive to potential constraints is key in supporting actors to realize intended goals and impacts (Koerner and Duda, 2021; Zurek et al., 2022a).

6 For example, Principle 6 guides R&I projects in managing natural resources in a sustainable and circular manner, thus requiring the consideration of sustainability and circularity in each thematic dimension of its sub-principles.

Building on this, the Taskforce recommended that theories of change be designed and conducted using systems thinking. Analyzing agrifood system actors' interactions with their socio-economic and biophysical environments can reveal overlooked outcomes and impact pathways. This is important because these interactions are often complex, non-linear, multi-relational, and have significant feedback effects (van Berkum et al., 2018). Hence, systems thinking can set a foundation for developing more holistic 'systems innovations'. When identifying the area for analysis within the system, the Taskforce posited that systems thinking be applied at different scales and from different angles covering all impacted actors and activities (Zurek et al., 2022b).

However, it was acknowledged that the complexity of agrifood systems impedes the immediate identification and measurement of all interdependencies and relations. Consequently, the Taskforce suggested a reflexive and adaptive approach for developing theories of change. Iterative data and results monitoring at strategic points facilitates learning and minimizes the risk of unintended consequences, allowing for course corrections (Beers and van Mierlo, 2017). Using a flexible and adaptive theory of change from an agrifood systems perspective continuously verifies that an innovation project aligns with its objectives under changing circumstances.

Principle 2: Design transparent and evidence-based innovation processes.
2.1. Information on innovation goals, key intended outcomes, and budgets publicly available.
2.2. Analysis of needed resources and capabilities, and the ability to obtain them.
2.3. Evidence-based processes including use of credible metrics.
2.4. Sharing of knowledge/insights, as appropriate, with others (public or private entities).

Transparency is recognized as an important factor for abetting accountability, enhancing traceability, supporting coordination, building trust, enhancing learning across sectors, and supporting socially responsible entrepreneurship and governance (Piechocki, 2004; Zakutniaia and Hayriyan, 2017; Gupta et al., 2020). While intellectual property rights need to be preserved, sharing some information on innovation processes allows others to review the cogency of the approach taken. In doing so, transparency promotes downward accountability by providing impacted stakeholders with an entry point for engagement.

In achieving transparency, determining needed resources and capabilities, as well as innovators' ability to obtain them, is important because resource limitations can strongly influence innovation outcomes and trade-offs. Transparency on resources and capabilities, particularly budget, has demonstrated positive impacts on human development (Cuadrado-Ballesteros and Bisogno, 2021) and was shown to strengthen innovation when coupled with security measures (Brown and Martinsson, 2019).

In abetting transparency, the Taskforce emphasized that innovation processes should be informed by credible and comprehensive evidence, ideally in the form of output and outcome metrics.[7] This is important for fostering the measurability and impact of innovations – not only as an end result, though also during the innovation process. Further, when actors work toward similar objectives (e.g., the SDGs), transparency and evidence-based decisions significantly improve impact, strengthening the case for information sharing. However, because innovation is so diverse, the Taskforce did not dictate specific metrics for use. In lieu of this, some metrics, proposed as standards in particular domains, can be used, for example on small-scale agriculture in the Global South (Musumba et al., 2017).

Principle 3: Conduct innovation processes in an inclusive and ethical manner.
3.1 Inclusive, fair, and transparent decision-making within innovation processes, ensuring all relevant stakeholders are included.
3.2. Fair and inclusive partnerships, and fair and ethical apportioning of benefits.
3.3. Active consideration of all relevant types of knowledge.
3.4. Ethically conducted innovation processes in compliance with human rights and other relevant international standards.

Considering inclusivity and ethics is paramount for agrifood innovations that often impact actors in complex ways (Leach et al., 2012; Klerkx and Rose, 2020). While human rights and other international standards form a widely recognized ethical foundation, current approaches to transform agrifood systems tend to be top-down and lack downwards accountability (UNSCN, 2019). In countering this, the Taskforce recommended including mechanisms for integrating inclusivity equity, and human rights, as well as other standards, into innovation processes, to prevent unintended consequences for vulnerable actors (Zurek et al., 2022b). This principle provides a starting point for going beyond 'participation tokenism' and 'box-checking' to address power asymmetries within innovation processes.

Here, multi-stakeholder or participatory processes are such mechanisms that can minimize negative impacts for minorities and other marginalized groups (Norström et al., 2020). Inclusion and participation of 'all relevant stakeholders' is a complex undertaking that can be limited by biases in stakeholder identification (Lelea et al., 2015). Still, it can also benefit innovation processes as diverse and inclusive work teams and partnerships tend to produce more innovative ideas (Fan and Swinnen, 2020; Asmal et al., 2022), much like the positive contributions of indigenous knowledge to conventional science (Uprety et al., 2012).

Principle 4: Address potential trade-offs, synergies, efficiencies, and unintended effects.
4.1. Transparent and systematic analysis of inputs, outputs, and agrifood system outcomes (Principles 5 to 8).
4.2. Transparent monitoring of winners and losers in innovation processes and outcomes (including unintended).

Standalone innovations are often designed to target specific agrifood system outcomes, meaning they can have unintended consequences and potentially be detrimental to sustainability within and beyond agrifood systems (Oliver et al., 2018; Herrero et al., 2021). Here, environmental and social outcomes are particularly likely to be neglected (Prasad et al., 2023) making managing and addressing such trade-offs a major challenge in advancing sustainability (Grass et al., 2020). Trade-off analyses, based on a clear theory of change from an agrifood systems perspective, and coupled with monitoring (Herrero et al., 2021; Zurek et al., 2021), can identify unintended consequences, including winners and losers of innovations as well as potential synergies and efficiencies.

7 Metrics are standards for measuring or evaluating that help to collect and display evidence.

Trade-off analyses enable open and honest discussions about the affected actors and why certain negative consequences may have to be accepted (Mausch et al., 2020). They can guide innovators in balancing the various outcomes that agrifood system actors want to bring about (Herforth et al., 2014; Kanter et al., 2018; Ridgway et al., 2019; UNSCN, 2019; Zhang et al., 2021) and help decision makers distribute trade-offs across geographies, groups of people or landscapes.

Principle 5: Consider contribution to improved food and nutrition security and health.
5.1. Food security.
5.2. Adequate nutrition.
5.3. OneHealth.

Principle 5 underlines the need for agrifood innovation to contribute to the outcomes of food security and adequate nutrition which are conventionally considered the core objectives of agrifood systems (Willett et al., 2019; Hebinck et al., 2021). However, most global regions' agrifood systems currently fall short in providing their populations with access to sufficient, safe, and nutritious food, to meet their food preferences and dietary needs necessary for a healthy life. Poor-quality diets cause multiple forms of malnutrition across the globe and constitute a main cause of global deaths (Lindgren et al., 2018; Lancet, 2020).

The Taskforce chose to complement these two sub-principles with the concept of OneHealth. While health in agrifood systems is often considered a result of food security and nutrition, agriculture's contribution to the emergence of zoonotic and transboundary diseases as well as antimicrobial resistance is increasingly recognized (Mackenzie and Jeggo, 2019). OneHealth constitutes "an integrated, unifying [systems] approach that aims to sustainably balance and optimize the health of people, animals and ecosystems" acknowledging their interdependence (FAO, OIE, WHO, 2021). In practice, the complementarity of these three sub-principles can be seen in the influence of OneHealth matters on food security (Garcia et al., 2020).

Principle 6: Consider contribution to sustainable and circular management and utilization of natural resources.
6.1. Biodiversity and integrated habitats.
6.2. Climate change mitigation.
6.3. Clean water.
6.4. Clean air.
6.5. Soil health.

Agrifood systems are dependent on a suitable climate and sufficient natural resource availability (Vermeulen et al., 2012a). However, their contribution to global environmental challenges including climate change and the degradation of natural resources such as biodiversity is substantial (Newbold et al., 2015; Crippa et al., 2021). The present dilemma evokes a strong call for more sustainable management and use of natural resources (Caron et al., 2018; Springmann et al., 2018; Rockström et al., 2020). Principle 6 and its sub-principles stress the importance of utilizing and managing natural resources in a sustainable and circular fashion.

Actors in agrifood innovation occupy a key role in shaping the transition toward sustainable natural resource management but they rarely follow environmental objectives (Prasad et al., 2023). Key here is the preservation of natural areas outside agrifood systems, which innovation can impact positively and negatively (Pirard and Belna, 2012; Villoria et al., 2014).[8] When innovators deliberately address the use and management of natural resources, positive contributions to environmental outcomes can be made [for example, mitigating biodiversity loss and global warming, ensuring clean air and water, and maintaining soil health (Hebinck et al., 2021)].[9] Moreover, the Taskforce highlighted that agriculture can contribute to regenerative processes in ecosystems which is especially relevant for – but not limited to – soil health (Schreefel et al., 2020).

In implementing these environmental considerations, circular approaches to natural resource management have the potential to alleviate environmental pressure (Muscio and Sisto, 2020). While there is a split between theory and practice in applying circular economy approaches in many fields, agrifood systems are a suitable ground for testing and implementing this concept, building on existing examples (Fassio and Tecco, 2019).

Principle 7: Consider contribution to a viable economy and sustainable livelihoods.
7.1. A viable agrifood systems sector contributing to the wider economy.
7.2. Secure and stable livelihoods of actors within the agrifood sector.

The agrifood sector remains of central importance to the economies of both the Global South and Global North (van der Ploeg et al., 2019). The businesses and public entities within those economies must innovate and take up transformative practices (FABLE, 2020; Herrero et al., 2020) to permit the economy's continuous harnessing of the various benefits arising from the agrifood sector. However, in a market-economy, sustainable innovations often have higher immediate production costs or require more initial investments. This means actors prioritizing private benefits (allocating resources in accordance with technical and allocative efficiencies), are less likely to apply sustainable innovations, even if public benefits are significant in the long run. However, the economic pathway to supporting welfare in a broad sense (which is the ultimate purpose of the economy) requires balancing market priorities with the creation and sustainable management of common goods (Johansson, 1991). Therefore, together with policy makers, innovators should consider how they can contribute to a healthy and stable economy at large, characterized by financial and price stability, the effective use of natural resources, and employment opportunities (among other characteristics).

A key issue in global agrifood systems is that the distribution of economic benefits is unequal. Negative developments (e.g., the COVID-19 pandemic) affect poor and marginalized populations more severely than their wealthier counterparts, especially in the Global South (Power et al., 2020; Swinnen and McDermott, 2020). In aiming to promote the mitigation of this inequality, the Taskforce included a principle emphasizing that the economic development and opportunities resulting from innovations need to create secure and

8 Mechanization and pesticides can drive increased deforestation through increased labor efficiency but increased productivity per hectare can simultaneously reduce the demand for additional land (Vadez et al., 2008).
9 Various tools exist to address the use and management of natural resources such as the drivers, pressures, state, impact, and response model of intervention (DPSIR) or the Tool for Agroecological Performance Evaluation (FAO, 2019).

stable livelihoods of actors. Innovation-driven productivity increases in farm labor will raise wages but also reduce labor demand. Many smallholder farmers will therefore be forced to switch to work outside the farm sector requiring a gradual transition based on education, mobility and urban development (FAO, 2014).

Principle 8: Consider contribution to an ethical, equitable, and adaptive agrifood system for current and future generations.
8.1. Human rights and decent working conditions.
8.2. Distribution of risks, benefits, and decision-making power within the household and along the value chain.
8.3. Inclusiveness.
8.4. Animal welfare.
8.5. Adaptation, that is equitable, including to climate and environmental change.

Ethics and equity represent a typical blind spot of innovation in agrifood systems (Hebinck et al., 2021; Herrero et al., 2021; Porciello et al., 2021; Zurek et al., 2021; Prasad et al., 2023), with the notable exemption of agroecological innovations (e.g., Barrios et al., 2020). Even with appropriate trade-off tools that guide social equity measurement, monitoring social objectives remains highly subjective and context-specific (Mottet et al., 2020). Due to their frequent neglect and the challenge of measurability, social outcomes of agrifood systems tend to include trade-offs that imply direct negative impacts on certain, often marginalized, groups such as smallholders, women, youth, conflict-affected people and refugees, elderly, disabled people, lower castes, religious and ethnic minorities as well as indigenous groups (McShane et al., 2011; Adams et al., 2014; Ellis et al., 2019). While Principle 8 shares thematic similarities with Principle 3 (ethical and equitable innovation processes), ethics and equity are also important as outcomes of innovation.

Human rights as well as safe and healthy working conditions are among the direct and indirect prerequisites for achieving all food system outcomes (Anderson, 2008) and innovation contributing to SAFS must therefore abide by them (Caron et al., 2018). Though, despite the transformative potential of national and international human rights systems, in practice, they are still not strong enough to effectively protect various agrifood actors from harm, especially from non-state actors (Kennedy and Liljeblad, 2016). This deficit is evident in the increasing precariousness of employment conditions in the agrifood sector which is closely linked to value chain power dynamics (Malanski et al., 2022a). Resultingly, innovations must consider how they are contributing to or affecting human rights and working conditions, both directly and indirectly.

Power imbalances between groups significantly influence decisions within agrifood systems including on innovations' risks, benefits, and associated decision-making power (Davila and Dyball, 2017). Therefore, innovations need to address inherited privileges and discursive disadvantages among the target population – and the intersectionality of these – including on economic, geographic, demographic, and other social levels (Allen, 2010; Kepkiewicz et al., 2015). Without these considerations, there is a considerable risk of agrifood systems transformation being carried out 'on the backs' of the poor and other marginalized groups (Mustafa et al., 2021; Davis et al., 2022). Currently, global value chains shift power away from local producers and toward retailers and supermarkets, mostly by establishing market standards (Barrett et al., 2020; Malanski et al., 2022a,b). Deliberately addressing power differences (e.g., in the household) makes agricultural interventions more impactful in various areas (Gillespie and van den Bold, 2017). Innovations and their complementary resources, such as access to land and markets, must therefore be created and distributed in a way that is accessible to low-income and other vulnerable populations (WRI, 2018). Inclusive innovation can help people escape intergenerational cycles of poverty, hunger, and malnutrition and contribute to education and political stability (Fan and Swinnen, 2020).

Animal welfare is another ethics-related outcome of agrifood systems with links to the sustainability and customer acceptability of a product (Blokhuis et al., 2019; Willett et al., 2019). Across all types of animal production systems, harmful conditions continue to constitute a problem despite the existence of protocols and indicators to monitor and avoid these (Fraser, 2008; Buller et al., 2020). Production in all countries can benefit from changes and innovations to alleviate poor conditions for animals (Temple and Manteca, 2020). While digital technologies hold promises in this areas, current animal welfare innovations still tend to put too much emphasis on physical health and productivity (Buller et al., 2020). The sustainability effects of related innovations are complex and need to be analyzed from an agrifood systems perspective (Broom, 2019).

6. Operationalizing the principles

Clear, simple, and straightforward operationalization is essential for ensuring a set of principles becomes a tool that facilitates transformational change. Current principles often do not overcome the status of a declaration of intent (Losch, 2022). Even in cases where organizations endorse principles or guidelines, without clear support and guidance on how to apply these in real work contexts, there is a risk that the principles will sit idle.

To solidify the link between theoretical guidelines and operationalized practice, the Taskforce developed a tool for operationalizing PARI. Three criteria were stipulated; the tool must allow for (1) an assessment of progress within any project or workstream, (2) a comparison across possible innovation options for strategic decision making, and (3) (in the longer term) benchmarking of one organization or company against others. To meet the first two criteria, PARI users must be able to assess their innovations against each principle. For the third, it must allow external users to conduct or review those assessments in a replicable manner. Adding to these criteria, the Taskforce called for guidance on addressing unintended consequences and trade-offs between principles, which was directly integrated as a principle of its own (Zurek et al., 2022b). Following this, the Taskforce developed a scoring system to support the integration of PARI into key decision-making processes. The scoring system allows users to assess the degree to which a (sub-)principle has been successfully applied to their innovation. To further assist users, the system is complemented by supporting documents, including a detailed step-by-step guide, a glossary, and a scoring template (CoSAI Secretariat, 2023).

Inspired by the scoring guideline of the Food and Agriculture Benchmark from the World Benchmarking Association (WBA, 2021), the Taskforce chose a four-step scoring system (0, 1, 2, 3) where each (sub-)principle is scored individually. Higher scores imply a more thorough and evidenced application of the (sub-)principles'

TABLE 1 Scoring system to assess the implementation of principles by an innovator/organization (CoSAI Secretariat, 2022).

Score	Level of implementation
0	No evidence that action has been taken to implement the principle.
1	*Some activities have been carried out in line with the principle*, but these are insufficient to justify a score of 2.
2	There is evidence that activities have been carried out in line with the principle and its sub-principles. *Information on the issues has been regularly and systematically collected and analyzed.*
3	There is evidence that activities have been carried out in line with the principle and its sub-principles. Information on the issues has been regularly and systematically collected and analyzed and *needed changes have been implemented.*

components. The lowest score (0) signifies that 'no action has been taken in implementing the (sub-)principle', while the highest score (3) indicates that all activities align with the (sub-)principle and are evidenced (Table 1). To achieve a score of 3, information on the innovation's application of the (sub-)principle must be regularly and systematically collected and analyzed and all needed changes must already be implemented at the point of scoring.

The overall score for a principle is the lowest *non-zero* score of all relevant sub-principles (e.g., if sub-principles are scored at 2 and 3, the overall score for that principle will be 2). However, if one of the sub-principles is scored zero, the overall score cannot be higher than 1 (e.g., if sub-principles are scored at 0, 2 and 3, the overall score for that principle will be 1).[10]

With guidance from the scoring template, users conduct the scoring using evidence from their innovation processes. This helps determine the degree to which a (sub-)principle has been fulfilled. Irrelevant sub-principles can be omitted from the scoring process if users are able to justify that choice and support it with evidence.

The scoring process helps users identify specific process or outcome areas that can be improved or where they require additional evidence (as the basis for any score higher than 1). Through iterative scoring, PARI become a potent management tool for course corrections over an innovation's project cycle. Users are guided to apply PARI from the ideation and design stages onwards and thereafter at strategic points (e.g., mid-term review, ex-post evaluation) depending on project duration and other characteristics.

The step-by-step guide (CoSAI Secretariat, 2023) informs users on additional aspects of PARI's application, such as the right assessment level (i.e., when the scope of a project is too narrow or too broad). It also includes a glossary, a frequently asked questions section, and introduces the *score aggregation* feature in more detail which is particularly relevant for integrating PARI on the level of organizations or larger programs. The latter aggregates scores from a selected number of projects where each principle is weighted proportionally to project budgets.

The scoring system and supporting documents form the overall operational approach of PARI. They guide individuals in organizations or companies pursuing agrifood innovation to apply each principle in the context of their work. These materials are essential to concretely transform operational practice. Nonetheless, it is the uptake of PARI in the sector that is pivotal for impact and requires further reflection and recommendations.

7. Actionable recommendations

Because CoSAI was an ephemeral Commission, ending in 2021, a new champion agency is required for improving PARI and for upscaling their use. Without a clear champion, there is a risk that PARI will only be adopted sporadically by individual organizations. Here, several recommendations for upscaling the use of PARI are presented.

An agreement to champion PARI, by an agency or set of agencies, is required to take them forward. Ideally, this should be an organization with a wide reach in the agrifood sector, convening power across relevant stakeholders, a long-term and normative mandate, and expertise in setting standards. United Nations organizations such as the Food and Agriculture Organization (FAO) would be suitable here, particularly because FAO already champions other Principles for the agriculture sector.[11] Other potential champions include organizations like CGIAR, which could bring together various research investors and innovators interested in the Global South, or the World Business Council for Sustainable Development (WBCSD), which could convene large companies in the food and agriculture space.

A key priority for the new lead agency would be to link PARI to new initiatives on tracking agrifood innovation. Transparent tracking of investment in agrifood innovation can incentivize public and private sector investors to focus on developing sustainable innovations that support agreed global goals (Compton et al., 2022). A key undertaking in this space is FAO's new Agrifood Technology and Innovation Outlook (FAO, 2022). In addition, the World Benchmarking Alliance conducts the 'Food and Agriculture Benchmark' – an assessment process that seeks to stimulate major agrifood companies to choose sustainable business practices throughout their operations. The benchmark currently does not integrate parameters on innovation providing an opportunity for PARI to complement it in the future (WBA, 2021).

The new lead agency would also have to further demarcate PARI's potential role in relation to existing tools and approaches in the agrifood sector. It would also allow for a more in-depth justification of the choices made regarding sub-principles beyond their general importance as outlined in this article. For example, sustainable value chain (SVC) development similarly addresses complex systems and various sustainability dimensions (FAO, 2014). However, in practice it often suffers from the key problem that PARI addresses: the neglect

10 More information and examples of how to fill in the scoring template can be found under (CoSAI Secretariat, 2023).

11 For example, the Principles for Responsible Agricultural Investment (CFS, 2014).

of social and environmental objectives. The typical perspective on the immediate value chain of a particular product also tends to exclude elements and entire subjects that go beyond this scope. In contrast to PARI, SVC approaches also prioritize other procedural properties and mechanisms such as commercial viability, governance and behavior change as well as the upgrading of value chain components and scalability (FAO, 2014). Although PARI facilitates scalability by guiding innovations to intended impacts (e.g., Principle 1), it does not guide scaling directly and allows users to adapt the details of their assessment to the appropriate scale in their context. This also differentiates it from other tools that focus on interventions at specific scales such as Verra's LandScale that is fitted for landscape-level assessments (LandScale, 2023).

Adapting PARI for use in the planning and reporting systems of large organizations – including by actors less interested in systems approaches to sustainability – will require further piloting and adaptation. Piloting to date has informed considerable improvements to the principles, but it has mostly been limited to enthusiastic, small-scale users. In the future, there is a risk of losing cohesion and comparability as different organizations express their preferences in prioritizing principles over others and interpreting scores differently. When working with users to refine PARI, the new champion must ensure that principles will be coherently applied across user types while also responding to user demands.

Overall, upscaling PARI requires a new lead agency that defines PARI's position in relation to other tools and makes improvements based on piloting on a large scale. Further work is also needed in the implementation of a systems perspective and the provision of assessment metrics (see Section 8).

8. Discussion

Researchers and innovators in agrifood systems must undergo a major shift in managing and thinking about innovation. They need to internalize and operationalize a systems perspective that reconciles the conventional focus on productivity increases with environmental and social objectives. To address this, a diverse international Taskforce of experts developed a set of principles and a complementary scoring system. By accounting for innovation processes (in Principles 1 to 4) and outcomes (Principles 5 to 8), PARI can guide innovators, researchers, and related actors such as investors in actualizing innovations that enable a transformation toward SAFS. Various questions and issues arise from this work that will hopefully be taken forward by others.

PARI is a highly flexible tool that aims to support different agrifood system actors and functions for various innovation types, stages and contexts at different scales. This broad applicability is a strength of PARI that enables them to address complex systems, but it also carries risks. Various aspects will determine eventual impact including the availability of context-specific guidance on implementing a systems perspective and selecting metrics, sufficient transparency, as well as a balanced approach to complexity.

Taking an agrifood systems perspective and thus considering multiple outcomes of an innovation was one of the central themes in discussions by the Taskforce. Still, PARI does not prescribe a specific framework because – depending on the innovation context – different frameworks imply different functionalities when assisting innovators. The principles only facilitate the identification of interdependencies rather than directly identifying them for the user. Given the centrality of agrifood systems thinking within PARI, it needs to be considered that some innovation actors tend to think in more linear and siloed manners (den Boer et al., 2021). Lack of experience in applying agrifood systems thinking can therefore be an obstacle to PARI's uptake and implementation.[12] A potential solution for this issue is the development of more context-specific guidance on complementary agrifood systems tools.

At this stage, matching 'credible' metrics to the type and stage of an innovation can be difficult (i.e., Principle 2). Assessing developmental impacts of interventions in complex environments (e.g., by adding up small results within a value chain) often only provides anecdotal evidence (FAO, 2014). While there have been some useful attempts to develop metrics for agrifood research (Musumba et al., 2017) more work is needed. An initial collection of over 300 existing metrics (unpublished: Yicong Luo, pers. comm.) and an expert discussion convened by CoSAI confirmed the lack of standards in this area as well as gaps in the areas of financial, policy and institutional innovations. A diversity of metrics is needed to cover various types and objectives of innovation at different stages and scales as well as from multiple stakeholder viewpoints, and with different levels of resources available for measurement. Ideally, users of PARI could choose from a large set of recommended metrics in order to monitor the four agrifood system outcome areas (Principles 5 to 8).[13] Individual indicators for each category of metrics could be flexible and tailored to organizational needs and data availability.

Another challenge is to establish sufficient transparency (Principle 2) among innovation-related actors that use PARI. When considering all four types of outcomes in agrifood systems, decisions on trade-offs are highly likely. Being transparent about why one domain has been prioritized over another can be challenging as actors usually have little incentives to elucidate negative aspects of their work. To the contrary, there is a lot of pressure to report positively on sustainability aspects depending on institutional, cultural and legal norms which may lead to 'greenwashing' (Coelho, 2023). Transparency in decision making is however of critical importance for PARI and, generally, for ensuring favorable outcomes for those affected by an innovation in the long term. As pointed out by Mausch et al. (2020), it is important to clarify societal values and thus the priorities given to certain principles, since trade-offs are inherent in the process of developing innovations.

When addressing the complexity and uncertainty regarding potential outcomes, relevant actors need to overcome the increased risk of 'paralysis by analysis' and be aware that accounting for multiple goals tends to make innovation processes and their management more complex, time consuming and onerous. PARI needs to tap into mechanisms that make the assessment process as accessible and straightforward as possible without reducing complexity to an extent that undermines functionality.

12 This limitation extends to trade-off analyses recommended under Principle 4.

13 The idea of a small set of high-level metrics may be attractive but assuming causality between an innovation and a high-level outcome (e.g., district-level poverty) is problematic.

The complexity of interdependencies furthermore poses the question whether innovators should only `consider' the potential unintended consequences or whether they also have to ensure they `do no harm' (possibly integrating mitigation measures). For either option, establishing practical processes and monitoring frameworks for organizations and companies needs careful consideration.

As discussed by the Taskforce, having a single index for PARI would allow actors to compare various innovations more easily (or projects that include several innovations) and thus, simplify the identification of those innovations with the highest potential for sustainable impact. However, aggregating scores across principles masks details that can contribute to an informed decision (e.g., specific strengths and weaknesses as indicated by individual principles). In addition, the question of how to aggregate the scores of distinct principles has no clear answer. Would organizations that prioritize certain (sub-)principles apply different weightings? There is a clear need for further reflection in this area.

The challenge of encouraging wider adoption of PARI needs further deliberation and other barriers will have to be explored along the way. Their integration into planning and decision-making processes will not be easy as current innovators typically do not apply a systems perspective. PARI are a promising tool in this space.

Author contributions

MZ led the writing efforts together with JW and JC and all provided substantial research and writing. AH and SC also contributed substantial research and writing while PL and PVVP co-chaired the TaskForce and provided comments and direction. PT and MH provided comments. All authors contributed to the article and approved the submitted version.

Taskforce

PL, PVVP, Dr. Aggrey Agumya, Mr. Alessandro Meschinelli, Dr. Charlotte Pavageau, Mr. Christopher Ian Brett, Dr. Daniel Walker, Dr. Dominik Klauser, Dr. Eugenia Saini, Dr. Geraldo Martha Junior, Prof. Dr. Giovanni Frajese, Mr. Hayden Montgomery, Mr. Ishmael Sunga, Dr. Jerry Glover, Dr. John McMurdy, Dr. José Joaquín Campos Arce, JC, Dr. Ken Chomitz, Dr. Latha Nagarajan, Ms. Lissa Glasgo, MH, Dr. Maurice Lorka, PT, Ms. Patricia Flores, Ms. Rachel Lambert, Dr. Ravi Ketharpal, Dr. Sonja Vermeulen, Dr. Tania Eulalia Martínez-Cruz, Ms. Viktoria de Bourbon de Parme, Dr. Walter Odhiambo.

Funding

This research communicated as part of this paper was commissioned and funded by the Commission on Sustainable Agriculture Intensification (CoSAI). CoSAI was initiated and supported by the CGIAR Research Program on Water, Land, and Ecosystems (WLE), funded by the CGIAR Trust Fund and other donors (https://cgiar.org/funders). CoSAI Commissioners are independent, and facilitated by a Secretariat based at the International Water Management Institute (IWMI) headquarters in Colombo, Sri Lanka. Partial funding support from Feed the Future Sustainable Intensification Innovation Lab funded by United States Agency for International Development (Cooperative Agreement # AID-OAA-L-14-00006). Contribution number 23-117-J from Kansas Agricultural Experiment Station.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1059063/full#supplementary-material

References

Adams, V., Pressey, R. L., and Stoeckl, N. (2014). Navigating trade-offs in land-use planning: integrating human well-being into objective setting. *Ecol. Soc.* 19:53. doi: 10.5751/ES-07168-190453

Allen, P. (2010). Realizing justice in local food systems. *Camb. J. Reg. Econ. Soc.* 3, 295–308. doi: 10.1093/cjres/rsq015

Anderson, M. D. (2008). Rights-based food systems and the goals of food systems reform. *Agric. Hum. Values* 25, 593–608. doi: 10.1007/s10460-008-9151-z

Asmal, L., Lamp, G., and Tan, E. J. (2022). Considerations for improving diversity, equity and inclusivity within research designs and teams. *Psychiatry Res.* 307:114295. doi: 10.1016/j.psychres.2021.114295

Barrett, C. B., Reardon, T., Swinnen, J., and Zilberman, D. (2020). Agri-food value chain revolutions in low-and middle-income countries. *J. Econ. Lit.* 58, 1–67. doi: 10.1257/jel.20201539

Barrios, E., Gemmill-Herren, B., Bicksler, A., Siliprandi, E., Brathwaite, R., Moller, S., et al. (2020). The 10 elements of agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. *Ecosyst. People* 16, 230–247. doi: 10.1080/26395916.2020.1808705

Beers, P. J., and van Mierlo, B. (2017). Reflexivity and learning in system innovation processes. *Sociol. Rural.* 57, 415–436. doi: 10.1111/soru.12179

Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I. D., de Haan, S., Prager, S. D., et al. (2019). When food systems meet sustainability – Current narratives and implications for actions. *World Dev.* 113, 116–130. doi: 10.1016/j.worlddev.2018.08.011

Blokhuis, H., Veissier, I., Miele, M., and Jones, B. (2019). "Safeguarding farm animal welfare" in *Sustainability certification schemes in the agricultural and natural resource sectors: outcomes for society and the environment*. ed. M. Vogt (London: Routledge), 132–154.

Broom, D. M. (2019). Animal welfare complementing or conflicting with other sustainability issues. *Appl. Anim. Behav. Sci.* 219:104829. doi: 10.1016/j.applanim.2019.06.010

Brouwer, I. D., McDermott, J., and Ruben, R. (2020). Food systems everywhere: Improving relevance in practice. *Glob. Food Sec.* 26:100398. doi: 10.1016/j.gfs.2020.100398

Brown, J. R., and Martinsson, G. (2019). Does transparency stifle or facilitate innovation? *Manag. Sci.* 65, 1600–1623. doi: 10.1287/mnsc.2017.3002

Buller, H., Blokhuis, H., Lokhorst, K., Silberberg, M., and Veissier, I. (2020). Animal welfare management in a digital world. *Animals* 10:1779. doi: 10.3390/ani10101779

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., et al. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* 22:408. doi: 10.5751/ES-09595-220408

Caron, P., Ferrero y de Loma-Osorio, G., Nabarro, D., Hainzelin, E., Guillou, M., Andersen, I., et al. (2018). Food systems for sustainable development: proposals for a profound four-part transformation. *Agron. Sustain. Dev.* 38:41. doi: 10.1007/s13593-018-0519-1

CFS (2014). *Principles for responsible investment in agriculture and food systems*. Rome: FAO Committee on World Food Security.

Coelho, G. de S. e F. (2023). ESG is in the eye of the beholder. Available at: https://run.unl.pt/handle/10362/148926 (Accessed June 20, 2023)

Compton, J., Stads, G.-J., Barrett, C. B., Herrero, M., Arndt, C., Prasad, P. V. V., et al. (2022). Global Tracking of Agrifood Research and Innovation for Meeting Food Security and Sustainable Development Goals. Available at: https://www.g20-insights.org/policy_briefs/resilient-food-systems-and-nature-positive-agricultural-production-that-adapts-to-climate-and-external-shocks/ (Accessed October 5, 2022)

COP26 (2021). The Global Action Agenda for Innovation in Agriculture. UN Climate Change Conference UK. Available at: https://webarchive.nationalarchives.gov.uk/ukgwa/20230313121411/https://ukcop26.org/the-global-action-agenda-for-innovation-in-agriculture/ (Accessed June 20, 2023)

CoSAI Secretariat (2022). CoSAI | Promoting innovation for transformative change in the Global South. CoSAI – Commission for Sustainable Agriculture Intensification. Available at: https://www.iwmi.cgiar.org/archive/cosai/index/ (Accessed June 20, 2023)

CoSAI Secretariat (2023). Principles for Agrifood Research and Innovation; Step-by-step guidance. Principles for Agrifood Research and Innovation; Step-by-step guidance. Available at: https://www.iwmi.cgiar.org/archive/cosai/principles-guide/ (Accessed June 20, 2023)

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* 2, 198–209. doi: 10.1038/s43016-021-00225-9

Cuadrado-Ballesteros, B., and Bisogno, M. (2021). The relevance of budget transparency for development. *Int. Rev. Adm. Sci.* doi: 10.1177/00208523211027525

Daskalova, G. N., Myers-Smith, I. H., Bjorkman, A. D., Blowes, S. A., Supp, S. R., Magurran, A. E., et al. (2020). Landscape-scale forest loss as a catalyst of population and biodiversity change. *Science* 368, 1341–1347. doi: 10.1126/science.aba1289

Davila, F., and Dyball, R. (2017). "Food systems and human ecology: An overview" in *Sustainability Science* (London: Routledge)

Davis, B., Lipper, L., and Winters, P. (2022). Do not transform food systems on the backs of the rural poor. *Food Sec.* 14, 729–740. doi: 10.1007/s12571-021-01214-3

Davis, B., Mane, E., Gurbuzer, L. Y., Caivano, G., Piedrahita, N., Schneider, K., et al. (2023). *Estimating global and country-level employment in agrifood systems*. Rome, Italy: FAO.

de Boon, A., Sandström, C., and Rose, D. C. (2022). Governing agricultural innovation: A comprehensive framework to underpin sustainable transitions. *J. Rural. Stud.* 89, 407–422. doi: 10.1016/j.jrurstud.2021.07.019

den Boer, A. C. L., Kok, K. P. W., Gill, M., Breda, J., Cahill, J., Callenius, C., et al. (2021). Research and innovation as a catalyst for food system transformation. *Trends Food Sci. Technol.* 107, 150–156. doi: 10.1016/j.tifs.2020.09.021

Downs, S. M., and Fox, E. L. (2021). Uneven decline in food system inequality. *Nat. Food* 2, 141–142. doi: 10.1038/s43016-021-00247-3

Ellis, E. C., Pascual, U., and Mertz, O. (2019). Ecosystem services and nature's contribution to people: negotiating diverse values and trade-offs in land systems. *Curr. Opin. Environ. Sustain.* 38, 86–94. doi: 10.1016/j.cosust.2019.05.001

Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research. *Glob. Environ. Chang.* 18, 234–245. doi: 10.1016/j.gloenvcha.2007.09.002

FABLE (2020). "Pathways to Sustainable Land-Use and Food Systems," in *2020 Report of the FABLE Consortium*. (Laxenburg and Paris: International Institute for Applied Systems Analysis (IIASA) and Sustainable Development Solutions Network (SDSN)).

Fan, S., and Swinnen, J. (2020). Reshaping food systems: The imperative of inclusion. International Food Policy Research Institute (IFPRI). Available at: https://econpapers.repec.org/bookchap/fprifpric/9780896293670_5f01.htm (Accessed September 13, 2022).

FAO (2014). Developing Sustainable Food Value Chains: Guiding Principles. Rome: FAO. Available at: https://www.fao.org/3/i3953e/i3953e.pdf (Accessed June 20, 2023)

FAO (2018). *Sustainable food systems concept and framework*. Rome, Italy: FAO. Available at: https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1160811/ (Accessed August 11, 2023).

FAO (2019). Tool for Agroecology Performance Evaluation (TAPE) – Test version: Process of development and guidelines for application. Rome, Italy: FAO. Available at: https://www.fao.org/documents/card/en/c/ca7407en/ (Accessed September 30, 2022).

FAO (2020). A Summary to Assess Synergies and Trade-offs Among the Twenty Interconnected Sustainable Food and Agriculture (SFA) Transactions. Available at: https://www.fao.org/3/ca9923en/ca9923en.pdf (Accessed August 11, 2023).

FAO (2022). Introducing the Agrifood Systems Technologies and Innovations Outlook. FAO. Available at: https://www.fao.org/documents/card/en/c/cc2506en (Accessed June 20, 2023)

FAO, IFAD, UNICEF, WFP, WHO (2021). *The State of Food Security and Nutrition in the World 2021*. Rome: FAO.

FAO, OIE, WHO (2021). *Joint Tripartite (FAO, OIE, WHO) and UNEP Statement – Tripartite and UNEP support OHHLEP's definition of "One Health"*. Rome, Italy.

Fassio, F., and Tecco, N. (2019). Circular Economy for Food: A Systemic Interpretation of 40 Case Histories in the Food System in Their Relationships with SDGs. *Systems* 7:43. doi: 10.3390/systems7030043

Foran, T., Butler, J. R. A., Williams, L. J., Wanjura, W. J., Hall, A., Carter, L., et al. (2014). Taking complexity in food systems seriously: an interdisciplinary analysis. *World Dev.* 61, 85–101. doi: 10.1016/j.worlddev.2014.03.023

Fraser, D. (2008). Toward a global perspective on farm animal welfare. *Appl. Anim. Behav. Sci.* 113, 330–339. doi: 10.1016/j.applanim.2008.01.011

Frison, E. A., Cherfas, J., and Hodgkin, T. (2011). Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. *Sustainability* 3, 238–253. doi: 10.3390/su3010238

Garcia, S. N., Osburn, B. I., and Jay-Russell, M. T. (2020). One Health for Food Safety, Food Security, and Sustainable Food Production. *Front. Sustain. Food Syst.* 4:1. doi: 10.3389/fsufs.2020.00001

Gillespie, S., and van den Bold, M. (2017). Agriculture, Food Systems, and Nutrition: Meeting the Challenge. *Global Chall.* 1:1600002. doi: 10.1002/gch2.201600002

Grass, I., Kubitza, C., Krishna, V. V., Corre, M. D., Mußhoff, O., Pütz, P., et al. (2020). Trade-offs between multifunctionality and profit in tropical smallholder landscapes. *Nat. Commun.* 11:1186. doi: 10.1038/s41467-020-15013-5

Gupta, A., Boas, I., and Oosterveer, P. (2020). Transparency in global sustainability governance: to what effect? *J. Environment. Policy Plan.* 22, 84–97. doi: 10.1080/1523908X.2020.1709281

Hebinck, A., Zurek, M., Achterbosch, T., Forkman, B., Kuijsten, A., Kuiper, M., et al. (2021). A Sustainability Compass for policy navigation to sustainable food systems. *Glob. Food Sec.* 29:100546. doi: 10.1016/j.gfs.2021.100546

Hekkert, M. P., Janssen, M. J., Wesseling, J. H., and Negro, S. O. (2020). Mission-oriented innovation systems. *Environ. Innov. Soc. Trans.* 34, 76–79. doi: 10.1016/j.eist.2019.11.011

Herforth, A., Frongillo, E. A., Sassi, F., Mclean, M. S., Arabi, M., Tirado, C., et al. (2014). Toward an integrated approach to nutritional quality, environmental sustainability, and economic viability: research and measurement gaps. *Ann. N. Y. Acad. Sci.* 1332, 1–21. doi: 10.1111/nyas.12552

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Benton, T. G., Bodirsky, B. L., et al. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nat. Food* 1, 266–272. doi: 10.1038/s43016-020-0074-1

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Bodirsky, B. L., Pradhan, P., et al. (2021). Articulating the effect of food systems innovation on the Sustainable Development Goals. *Lancet Planetary Health* 5, e50–e62. doi: 10.1016/S2542-5196(20)30277-1

HLPE (2019). Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. Available at: https://www.fao.org/3/ca5602en/ca5602en.pdf; https://www.fao.org/family-farming/detail/en/c/1263887/ (Accessed September 30, 2022)

Holt-Gimenez, E., and Patel, R. (2012). *Food rebellions: crisis and the hunger for justice*. Oakland, CA: Food First Books.

Ingram, J. (2011). A food systems approach to researching food security and its interactions with global environmental change |. *SpringerLink* 3, 417–431. doi: 10.1007/s12571-011-0149-9

Ingram, J., and Zurek, M. (2018). "Food Systems Approaches for the Future" in *Agriculture & Food Systems to 2050 World Scientific Series in Grand Public Policy Challenges of the 21st Century* (Singapore: World Scientific), 547–567.

International Energy Agency (2022). World Energy Outlook 2022 – Analysis. IAE. Available at: https://www.iea.org/reports/world-energy-outlook-2022 (Accessed June 20, 2023)

Jacobi, J., Villavicencio Valdez, G. V., and Benabderrazik, K. (2021). Towards political ecologies of food. *Nat Food* 2, 835–837. doi: 10.1038/s43016-021-00404-8

Johansson, P.-O. (1991). An Introduction to Modern Welfare Economics. Cambridge University Press. Available at: https://econpapers.repec.org/bookchap/cupcbooks/9780521356954.htm (Accessed June 20, 2023)

Kanter, D. R., Musumba, M., Wood, S. L. R., Palm, C., Antle, J., Balvanera, P., et al. (2018). Evaluating agricultural trade-offs in the age of sustainable development. *Agric. Syst.* 163, 73–88. doi: 10.1016/j.agsy.2016.09.010

Kennedy, A., and Liljeblad, J. (2016). *Food systems governance: challenges for justice, equality and human rights*. London: Routledge.

Kepkiewicz, L., Chrobok, M., Whetung, M., Cahuas, M., Gill, J., Walker, S., et al. (2015). Beyond Inclusion: Toward an Anti-colonial Food Justice Praxis. *J. Agric. Food Syst. Commun. Dev.* 5, 99–104. doi: 10.5304/jafscd.2015.054.014

Klerkx, L., and Begemann, S. (2020). Supporting food systems transformation: The what, why, who, where and how of mission-oriented agricultural innovation systems. *Agric. Syst.* 184:102901. doi: 10.1016/j.agsy.2020.102901

Klerkx, L., and Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? *Glob. Food Sec.* 24:100347. doi: 10.1016/j.gfs.2019.100347

Knol, A. B., Slottje, P., van der Sluijs, J. P., and Lebret, E. (2010). The use of expert elicitation in environmental health impact assessment: a seven step procedure. *Environ. Health* 9, 1–16. doi: 10.1186/1476-069X-9-19

Koerner, J., and Duda, A. (2021). Transformative end-to-end innovation (E2EI) in a new era for food and climate: Insights and key actions supporting institutional change. Available at: https://cgspace.cgiar.org/handle/10568/113956 (Accessed March 7, 2022)

Lambin, E., and Thorlakson, T. (2018). Sustainability Standards: Interactions Between Private Actors, Civil Society, and Governments. *Ann. Rev. Environ. Resour.* 43:369. doi: 10.1146/annurev-environ-102017-025931

Lancet, T. (2020). Global health: time for radical change? *Lancet* 396:1129. doi: 10.1016/S0140-6736(20)32131-0

LandScale (2023). LandScale – Powering Landscape Sustainability. Available at: https://www.landscale.org/ (Accessed June 20, 2023)

Leach, M., Rockström, J., Raskin, P., Scoones, I., Stirling, A., Smith, A., et al. (2012). Transforming innovation for sustainability. *Ecol. Soc.* 17:211. doi: 10.5751/ES-04933-170211

Lelea, M. A., Roba, G. M., Christinck, A., and Kaufmann, B. (2015). All relevant stakeholders: A literature review of stakeholder analysis to support inclusivity of innovation processes in farming and food systems. Proceedings of the 12th European IFSA Symposium, Newport, UK, 12–15.

Lindgren, E., Harris, F., Dangour, A. D., Gasparatos, A., Hiramatsu, M., Javadi, F., et al. (2018). Sustainable food systems—a health perspective. *Sustain. Sci.* 13, 1505–1517. doi: 10.1007/s11625-018-0586-x

Losch, B. (2022). Decent Employment and the Future of Agriculture. How Dominant Narratives Prevent Addressing Structural Issues. *Front. Sustain. Food Syst.* 6:862249. doi: 10.3389/fsufs.2022.862249

Mackenzie, J. S., and Jeggo, M. (2019). The One Health Approach—Why Is It So Important? *Trop. Med. Infect. Dis.* 4:88. doi: 10.3390/tropicalmed4020088

Malanski, P. D., Schiavi, S. M. D. A., Dedieu, B., and Damansceno, J. C. (2022b). International research on labor in agri-food value chains: A bibliometric review from web of science. *Front. Sustain. Food Syst.* 6:852178. doi: 10.3389/fsufs.2022.852178

Malanski, P. D., Schiavi, S., Dedieu, B., and Damasceno, J. C. (2022a). Labor in agrifood value chains: a scientometric review from Scopus. *Int. Food Agribus. Manag. Rev.* 25, 449–468. doi: 10.22434/IFAMR2021.0066

Mannar, V., Micha, R., Allemandi, L., Afshin, A., Baker, P., Battersby, J., et al. (2020). 2020 Global nutrition report: action on equity to end malnutrition. Available at: https://globalnutritionreport.org/reports/2020-global-nutrition-report/ (Accessed June 20, 2023)

Mausch, K., Hall, A., and Hambloch, C. (2020). Colliding paradigms and trade-offs: Agri-food systems and value chain interventions. *Glob. Food Sec.* 26:100439. doi: 10.1016/j.gfs.2020.100439

Mazzucato, M., Kattel, R., and Ryan-Collins, J. (2020). Challenge-Driven Innovation Policy: Towards a New Policy Toolkit. *J. Ind. Compet. Trade* 20, 421–437. doi: 10.1007/s10842-019-00329-w

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., et al. (2019). Food Security. Available at: https://policycommons.net/artifacts/458644/food-security/1431487/ (Accessed June 20, 2023)

McShane, T. O., Hirsch, P. D., Trung, T., Songorwa, A. N., Kinzig, A., Monteferri, B., et al. (2011). Hard choices: Making trade-offs between biodiversity conservation and human well-being. *Biol. Conserv.* 144, 966–972. doi: 10.1016/j.biocon.2010.04.038

Mottet, A., Bicksler, A., Lucantoni, D., De Rosa, F., Scherf, B., Scopel, E., et al. (2020). Assessing transitions to sustainable agricultural and food systems: a tool for agroecology performance evaluation (TAPE). *Front. Sustain. Food Syst.* 4:579154. doi: 10.3389/fsufs.2020.579154

Muscio, A., and Sisto, R. (2020). Are agri-food systems really switching to a circular economy model? Implications for European research and innovation policy. *Sustainability* 12:5554. doi: 10.3390/su12145554

Mustafa, M. A., Mabhaudhi, T., Avvari, M. V., and Massawe, F. (2021). "Chapter 2 – Transition toward sustainable food systems: a holistic pathway toward sustainable development" in *Food Security and Nutrition*. ed. C. M. Galanakis (Cambridge, MA: Academic Press), 33–56.

Musumba, M., Grabowski, P., Palm, C., and Sieglinde, S. (2017). Guide for the Sustainable Intensification Assessment Framework. USAID, Kansas State University Available at: https://www.k-state.edu/siil/documents/docs_siframework/Guide%20for%20SI%20Assessment%20Framework%20-%2010.24.17.pdf (Accessed August 11, 2023).

Newbold, T., Hudson, L. N., Hill, S. L., Contu, S., Lysenko, I., Senior, R. A., et al. (2015). Global effects of land use on local terrestrial biodiversity. *Nature* 520, 45–50. doi: 10.1038/nature14324

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., et al. (2020). Principles for knowledge co-production in sustainability research. *Nat. Sustain.* 3, 182–190. doi: 10.1038/s41893-019-0448-2

OECD (2019). *Trends and Drivers of Agri-environmental Performance in OECD Countries*. Paris: OECD.

Oliver, T. H., Boyd, E., Balcombe, K., Benton, T. G., Bullock, J. M., Donovan, D., et al. (2018). Overcoming undesirable resilience in the global food system. *Global Sustain.* 1:e9. doi: 10.1017/sus.2018.9

Piechocki, R. (2004). Transparency of Annual Sustainability Reports. *Corp. Reputat. Rev.* 7, 107–124. doi: 10.1057/palgrave.crr.1540215

Pirard, R., and Belna, K. (2012). Agriculture and Deforestation: is REDD+ Rooted in evidence? *Forest Policy Econ.* 21, 62–70. doi: 10.1016/j.forpol.2012.01.012

Porciello, J., Lipper, L., Bourne, T., Ivanina, M., Lin, S., and Langleben, S. (2021). Mining the gaps: Using machine learning to map a million data points from agricultural research from the global south. Colombo, Sri Lanka: Commission for Sustainable Agriculture Intensification (CoSAI). Available at: https://cgspace.cgiar.org/handle/10568/119437 (Accessed August 11, 2023).

Power, T., Wilson, D., Best, O., Brockie, T., Bourque Bearskin, L., Millender, E., et al. (2020). COVID-19 and Indigenous Peoples: An imperative for action. *J. Clin. Nurs.* 29, 2737–2741. doi: 10.1111/jocn.15320

Prasad, P. V. V., Bhatnagar, N., Bhandari, V., Jacob, G., Narayan, K., Echeverría, R., et al. (2023). Patterns of investment in agricultural research and innovation for the Global South, with a focus on sustainable agricultural intensification. *Front. Sustain. Food Syst.* 7:8949. doi: 10.3389/fsufs.2023.1108949

Ridgway, E., Baker, P., Woods, J., and Lawrence, M. (2019). Historical Developments and Paradigm Shifts in Public Health Nutrition Science, Guidance and Policy Actions: A Narrative Review. *Nutrients* 11:531. doi: 10.3390/nu11030531

Rockström, J., Edenhofer, O., Gaertner, J., and DeClerck, F. (2020). Planet-proofing the global food system. *Nat. Food* 1, 3–5. doi: 10.1038/s43016-019-0010-4

Sage, C. (2018). "Agro-food systems," in *Companion to environmental studies*. (Abingdon, Oxon, UK: Routledge), 486–490.

Schreefel, L., Schulte, R. P. O., de Boer, I. J. M., Schrijver, A. P., and van Zanten, H. H. E. (2020). Regenerative agriculture – the soil is the base. *Glob. Food Sec.* 26:100404. doi: 10.1016/j.gfs.2020.100404

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., et al. (2018). Options for keeping the food system within environmental limits. *Nature* 562, 519–525. doi: 10.1038/s41586-018-0594-0

Swinnen, J., and McDermott, J. (2020). COVID-19 and Global Food Security. *EuroChoices* 19, 26–33. doi: 10.1111/1746-692X.12288

Temple, D., and Manteca, X. (2020). Animal welfare in extensive production systems is still an area of concern. *Front. Sustain. Food Syst.* 4:545902. doi: 10.3389/fsufs.2020.545902

UN DESA (2021). World Social Report 2021: Reconsidering Rural Development. UN Department of Economic and Social Affairs. Available at: http://desapublications.un.org/publications/world-social-report-2021-reconsidering-rural-development (Accessed September 30, 2022)

UNSCN (2019). UNSCN Nutrition 44: Food environments: Where people meet the food system. Rome: United Nations Standing Committee on Nutrition. Available at: https://www.unscn.org/en/resource-center?idnews=1976 (Accessed September 30, 2022)

Uprety, Y., Asselin, H., Bergeron, Y., Doyon, F., and Boucher, J.-F. (2012). Contribution of traditional knowledge to ecological restoration: Practices and applications. *Écoscience* 19, 225–237. doi: 10.2980/19-3-3530

Vadez, V., Reyes-García, V., Huanca, T., and Leonard, W. R. (2008). Cash Cropping, Farm Technologies, and Deforestation: What are the Connections? A Model with Empirical Data from the Bolivian Amazon. *Hum. Organ.* 67, 384–396. doi: 10.17730/humo.67.4.45164623415rp7n8

van Berkum, S., Dengerink, J., and Ruben, R. (2018). The food systems approach: sustainable solutions for a sufficient supply of healthy food. *The Hague Wageningen Econ. Res.* 10:18174. doi: 10.18174/451505

van der Ploeg, J. D., Barjolle, D., Bruil, J., Brunori, G., Costa Madureira, L. M., Dessein, J., et al. (2019). The economic potential of agroecology: Empirical evidence from Europe. *J. Rural. Stud.* 71, 46–61. doi: 10.1016/j.jrurstud.2019.09.003

Vermeulen, S. J., Aggarwal, P. K., Ainslie, A., Angelone, C., Campbell, B. M., Challinor, A. J., et al. (2012a). Options for support to agriculture and food security under climate change. *Environ. Sci. Pol.* 15, 136–144. doi: 10.1016/j.envsci.2011.09.003

Vermeulen, S. J., Campbell, B. M., and Ingram, J. S. I. (2012b). Climate Change and Food Systems. *Annu. Rev. Environ. Resour.* 37, 195–222. doi: 10.1146/annurev-environ-020411-130608

Villoria, N. B., Byerlee, D., and Stevenson, J. (2014). The effects of agricultural technological progress on deforestation: what do we really know? *Appl. Econ. Perspect. Policy* 36, 211–237. doi: 10.1093/aepp/ppu005

Waggoner, J., Carline, J. D., and Durning, S. J. (2016). Is there a consensus on consensus methodology? Descriptions and recommendations for future consensus research. *Acad. Med.* 91, 663–668. doi: 10.1097/ACM.0000000000001092

WBA (2021). *The Methodology for the 2021 Food and Agriculture Benchmark*. Amsterdam: World Benchmarking Alliance.

Webb, P., Benton, T. G., Beddington, J., Flynn, D., Kelly, N. M., and Thomas, S. M. (2020). The urgency of food system transformation is now irrefutable. *Nat. Food* 1, 584–585. doi: 10.1038/s43016-020-00161-0

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

WRI (2018). How to Sustainably Feed 10 Billion People by 2050, in 21 Charts. World Resources Institute. Available at: https://www.wri.org/blog/2018/12/how-sustainably-feed-10-billion-people-2050-21-charts (Accessed September 12, 2019)

WWF (2021). Investors can now assess the impact of financial portfolios on nature, people, and society. World Wildlife Fund. Available at: https://wwf.panda.org/wwf_news/?3012916/Investors-can-now-assess-the-impact-of-financial-portfolios-on-nature-people-and-society (Accessed June 20, 2023)

Zakutniaia, A., and Hayriyan, A. (2017). Transparency as competitive advantage of innovation driven companies. *BEL*, 46–54. doi: 10.21272/bel.2017.1-06

Zhang, X., Yao, G., Vishwakarma, S., Dalin, C., Komarek, A. M., Kanter, D. R., et al. (2021). Quantitative assessment of agricultural sustainability reveals divergent priorities among nations. *One Earth* 4, 1262–1277. doi: 10.1016/j.oneear.2021.08.015

Zurek, M., Hebinck, A., and Selomane, O. (2021). Looking across diverse food system futures: Implications for climate change and the environment. *Q Open* 1:1. doi: 10.1093/qopen/qoaa001

Zurek, M., Hebinck, A., and Selomane, O. (2022a). Climate change and the urgency to transform food systems. *Science* 376, 1416–1421. doi: 10.1126/science.abo2364

Zurek, M., Hebinck, A., Wirths, J., Al-Malalha, M., and Crawford, S. (2022b). Task Force on Principles and Metrics for Innovation in Sustainable Agri-food Systems: Final Report. Commission on Sustainable Agriculture Intensification Available at: https://cgspace.cgiar.org/handle/10568/119439 (Accessed May 4, 2022)

Zurek, M., Ingram, J., Sanderson Bellamy, A., Goold, C., Lyon, C., Alexander, P., et al. (2022c). Food system resilience: concepts, issues, and challenges. *Annu. Rev. Environ. Resour.* 47, 511–534. doi: 10.1146/annurev-environ-112320-050744

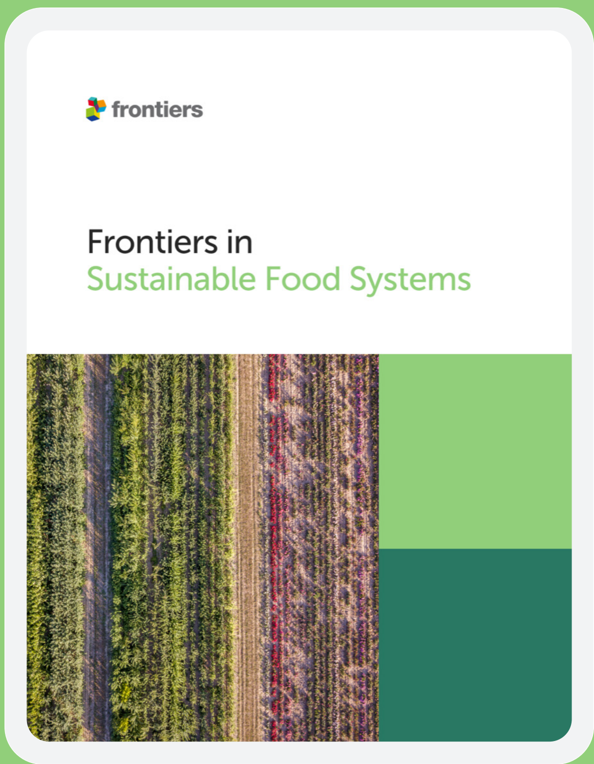
Frontiers in
Sustainable Food Systems

Exploring sustainable solutions to global food security

Aligned with the UN Sustainable Development Goals, this journal explores the intersection of food systems, science and practice of sustainability including its environmental, economic and social justice dimensions.

Discover the latest Research Topics

See more →



Frontiers

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

Contact us

+41 (0)21 510 17 00
frontiersin.org/about/contact