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Achieving Agricultural Breakthrough:

A deep dive into seven technological areas

Achieving Agricultural Breakthrough

Deep Dive into Seven Technological Areas

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Citation: Mukherji, A., C. Arndt, J. Arango, F. Flintan, J. Derera, W. Francesconi, S. Jones, A.M Loboguerrero, D. Merrey, J. Mockshell, M. Quintero, D. G. Mulat, C. Ringler, L. Ronchi, M.E.N. Sanchez, T. Sapkota, S. Thilsted (2023). ***Achieving agricultural breakthrough: A deep dive into seven technological areas*****, CGIAR, Montpellier,** France 138 pp. *https://hdl.handle.net/10568/131852*

Keywords:: agriculture / GHG emissions / climate resilience / adaptation / mitigation / technology / just-transition / breakthrough principles / pathways / fertilisers / nitrogen use efficiency / precision fertilisation / low emissions fertilisers / inhibitors / nitrogen fixation / alternative proteins / nutrition / food loss and waste / genetic innovations / crop breeding / livestock breeding / livestock / methane emissions / manure / climate-smart livestock / agroecology / sustainable agriculture / enabling environment / digital services / weather forecasts / crop insurance / agricultural advice / inequity / gender / international collaborations

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List of Abbreviations and Acronyms

3-NOP	3-nitrooxypropanol
ABPP	Africa Biogas Partnership Programme
ACE	Angiotensin-converting enzyme
AD	Anaerobic digestion
ADA	Appui au développement autonome
ADB	Asian Development Bank
ADGG	African Dairy Genetic Gain
AE	Agroecology
AFA	Asian Farmers' Association for Sustainable Rural Development
AfDB	African Development Bank
AFOLU	Agriculture, Forestry, and Other Land Use
AFSA	Alliance Food Sovereignty in Africa
AGNES	African Group of Negotiators Expert Support
AGRA	Allance for a Green Revolution in Africa
AI	Artificial Intelligence
AIM4C	Aim for Climate
ANI	Asian News International
AOCC	African Orphan Crops Consortium
APAARI	Asia-Pacific Association of Agricultural Research Institutions
APHLIS	African Postharvest Losses Information System
API	Alternative Protein International
APNI	African Plant Nutrition Institute
ASARECA	The Association for Strengthening Agricultural Research in Eastern and Central Africa
ASF	Animal source foods
A-WEAI	Abbreviated Women's Empowerment in Agriculture Index
BCR	Benefit to cost ratio
BMGF	Bill and Melinda Gates Foundation
BNF	Biological nitrogen fixation
BNI	Biological Nitrification inhibitors
BSF	Black Soldier Flies
CAADP	Comprehensive Africa Agriculture Development Programme
CADENA	Componente de Atención a Desastres Naturales
CADN	Componente de Atención a Desastres Naturales
CAP	Common Agricultural Policy
CBBP	Community Based Breeding Programs
CBD	Convention on Biological Diversity
CCA	Clean Cooking Alliance
CCAC	Climate and Clean Air Coalition
CCAFS	Climate Change Agriculture and Food Security
CCS	Carbon capture and storage
CFAI	Confederation of Farmers Associations of India
CF-Rice	Carbon footprints of rice
CGIAR	Consultative Group on Agricultural Research
CH_4	Methane
CH_4e	Methane equivalent
CIAT	International Center for Tropical Agriculture
CIFOR	Center for International Forestry Research
CIMMYT	International Maize and Wheat Improvement Center
CIP	International Potato Center
CIRAD	French Agricultural Research Centre for International Development
CO^2-eq	carbon dioxide equivalent
COP26	26th Conference of Parties to the UNFCCC
CORAF/ WECARD	West and Central African Council for Agricultural Research
CSA	Climate Smart Agriculture
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTA	Technical Centre for Agricultural and Rural Cooperation
D4Ag	Digitalization of African Agriculture
DACS	Digital Agricultural and Climate Services
DCD	Dicyandiamide
DMPP	Dimethylpyrazole phosphate
EEF	Enhanced efficiency fertilizers
EMBRAPA	Brazilian Agricultural Research Corporation
EU-28	European Union
F-ACT and B-ACT	Farm and Business Agroecology Criteria Tools
FAO	Food and Agriculture Organization
FAOSTAT	The Food and Agriculture Organization Corporate Statistical Database
FARA	Forum for Agricultural Research in Africa
FBDGs	Food-based dietary guidelines
FCDO	Foreign, Commonwealth and Development Office
FLAG	Forest, Land and Agriculture
FLW	Food loss and waste
FSAs	Food System Actors
GAP	Good Agricultural Practice
GBF	Global Biodiversity Framework
GCF	Green Climate Fund
GCIN	Global Crop Improvement Network
GEF	Global Environment Facility at United Nations Environment Programme
GFAR	Global Forum on Agricultural Research and Innovation
GFI	Good Food Institute
GFSI	Global Food Safety Initiative
GGRASP	Global GAP Risk Assessment on Social Practice
GHG	Greenhouse gas
GIFLWR	Global Initiative on Food Loss and Waste Reduction
GIS	Geographic information systems
GIZ	The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

GMO	Genetically modified organisms
GODAN	Global Open Data for Agriculture and Nutrition
GRA	Global Research Alliance on Agricultural Greenhouse Gases
GRASP	Global GAP Risk Assessment on Social Practice
GTCO^{2}e	Giga tonnes of carbon dioxide equivalent
GWAS	Genome-wide association studies
HICs	High income countries
HLPE-FSN	High-Level Panel of Experts on Food Security and Nutrition
ICAR	Indian Council of Agricultural Research
ICARDA	International Center for Agricultural Research in Dry Areas
ICIPE	The International Centre of Insect Physiology and Ecology
ICRAF	World Agroforestry Centre
ICT	information and communications technology
IDBs	International Development Banks
IDRC	The International Development Research Centre
IEA	International Energy Agency
IFA	International Fertilizer Association
IFAD	International Fund for Agricultural Development
IFAP	International Federation of Agricultural Producers
IFC	International Finance Corporation
IFDC	International Fertilizer Development Centre
IFIs	International Financial Institutions
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
INI	International Nitrogen Initiative
INMS	International Nitrogen Management System
IP	Intellectual property
IPCC	The Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRRI	International Rice Research Institute
ISFM	Integrated Soil Fertility Management
ISO	International Organization for Standardization
ISTA	International Seed Testing Association
ITU	The International Telecommunication Union
IWMI	International Water Management Institute
KALRO	Kenya Agricultural and Livestock Research Institute
LICs	Low income countries
LMICs	Low and medium income countries
MACS-G20	Meetings of Agricultural Chief Scientists of G20 States
MDBs	Multilateral Development Banks
MLN	Maize lethal necrosis
MRV	measurement, reporting and verification
MSU	Michigan State University
Mt	Mega tonnes
MT	Million tonnes
Mt CO^{2}e	Metric tons of carbon dioxide equivalent
N_2O	Nitous oxide
NARES	National agricultural research and extension agencies
NDCs	Nationally Determined Contributions
NFU	National Farmers Union
NGOs	Non governmental organisations
NH_3	Ammonia
NH_4	Ammonium
NH_4+	Ammonium cation
NO_3–	Nitrate ion
NUE	Nitrogen use efficiency
OECD	Organisation for Economic Co-operation and Development.
PAFO	Pan African Farmers Organization
PD	Policy Dialogue on Transition to Sustainable Agriculture
PIK	Potsdam Institute for Climate Impact Research
PPPs	Public private partnerships
QTL	Quantitative trait loci
RCT	Randomized control trial
RD&D	Research, development and demonstration
RSB	Roundtable on Sustainable Biomaterials
SADC-FANR	South African Development Community Food Agriculture and Natural Resources
SADMS	South Asia Drought Monitoring System
SAI	Sustainable Agriculture Initiative Platform
SAVE FOOD	Initiative by FAO
SDC	Swiss Agency for Development and Cooperation
SDGs	Sustainable Development Goals
SFS	Sustainable Food Systems (SFS) Programme
SLU	Swedish University of Agricultural Sciences
SMEs	Small and medium-sized enterprises
SNMI	Sustainable Nitrogen Management Index
SOCLA	La Sociedad Científica Latinoamericana de Agroecología
SSNM	site- specific nutrient management
TAPE	Tool for Agroecology Performance Evaluation
TNC	The Nature Conservancy
TPP	Transformative Partnership Platform for Agroecology
UAS	University of Agricultural Sciences
UK	United Kingdom
UNCTD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Programme
UNIDO	United Nations Industrial Development Organization
UPOV	Union for the Protection of New Varieties of Plants
USA	United States of America
USAID	United States Agency for International Development
USC	Universidade de Santiago de Compostela
USD	United States Dollar
USDA	The United States Department of Agriculture
VRF	Variable rate fertilisation
WAAPP	West Africa Agricultural Productivity Program
WAVA	Weighted average varietal age
WBCSD	World Business Council for Sustainable Development
WFBRI	Wageningen Food and Biobased Research Institute
WFP	World Food Programme
WHO	World Health Organisation
WRI	World Research Institute
WRMS	Waste and Resource Management System
WTO	World Trade Organization.
WUE	Water use efficiency

Executive summary

The breakthrough objective for the food and agriculture sector is to make climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by 2030 (IEA, 2022). The world is 1.1°C warmer than pre-industrial times due to human-caused greenhouse gas (GHG) emissions. The effects of climate change are felt globally and are projected to worsen with further warming. The agrifood sector is particularly vulnerable to climate change, with losses and damages occurring throughout the value chain due to extreme weather events like high temperatures, droughts, and floods. Small-scale farmers in the Global South are especially at risk, and current efforts to adapt to climate change are not sufficient. To minimise the impacts of climate change, it is crucial to stay within the 1.5°C to 2°C temperature goals set by the Paris Agreement. Achieving this requires immediate and deep reductions in emissions across all sectors, including the agrifood sector, which accounts for almost one-third of all GHG emissions (IPCC, 2023c), within a broader framework of just transitions that safeguards the interests of smallholder producers, particularly those in the Global South who are most at risk.

The agrifood sector requires transformative changes (or breakthroughs) to reduce emissions and ensure food and nutrition security without damaging natural resources while also making smallholder producers more climate-resilient. However, the sector's inherent diversity makes technologies and approaches for reducing GHG emissions and building long-term climate resilience very context specific, which in turn requires careful analysis of trade-offs and synergies across various dimensions. A bundle of innovations in practices, technologies, policies and financing, across various subcomponents of the agricultural value chain, are needed to achieve these breakthrough objectives. We use the term technological areas and approaches throughout the report to describe these innovations in practices, technologies, policies and financing.

The agriculture chapter of the 2022 Breakthrough Agenda Report (IEA, 2022) identified seven technological areas and approaches to achieve breakthroughs in the agriculture sector. This report provides a detailed analysis of these seven technological areas and approaches by documenting the latest scientific advancements in each one and evaluating how these fare across the four principles outlined in the 2022 agriculture chapter. Additionally, this report considers the different geographical and socioeconomic contexts in which these four principles apply and accordingly qualifies them further. The modified principles proposed are:

- Agricultural productivity and incomes in low and middle-income countries (LMICs) must increase sustainably, in order to achieve food and nutrition security and healthy and sustainable diets for all;
- The sector must reduce GHG emissions, and depending on technologies and approaches and geographies, these can be reductions in emissions intensity, or absolute emissions reductions, or both, with the ultimate aim of reducing absolute emissions;

- Soil, water, biodiversity and natural ecosystems must be safeguarded across all geographies, including through a focus on healthy ecosystems; ;
- The sector must adapt and build resilience to climate change, including through approaches that promote inclusion and social safety nets for the poor and vulnerable small holder producers in the Global South.

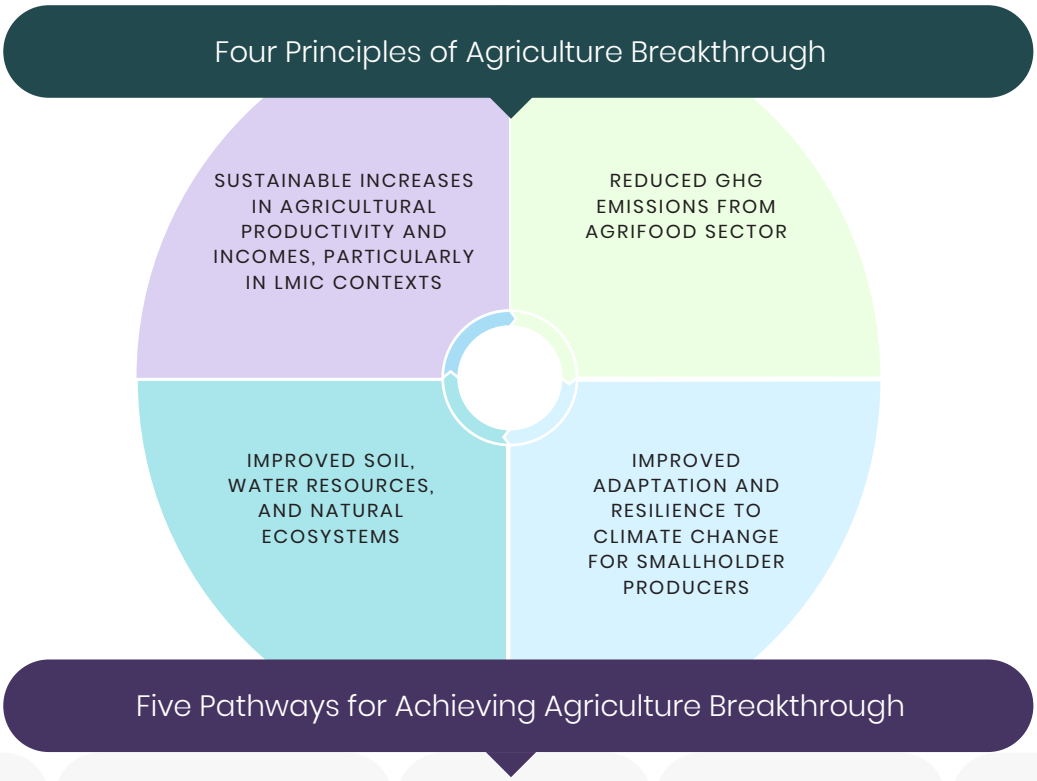
In this report, we additionally chart these seven technological areas and approaches across five pathways. These pathways (interdependent with each other and with the four principles of the breakthrough mentioned above) are:

1. Reducing unsustainable consumption where such consumption has harmful effects on health, climate and the environment. Examples include (but are not limited to): alternative proteins to address high meat consumption in high-income countries (HICs); reducing the use of fertilisers and improving nitrogen use efficiency (NUE) in regions of excess application, by implementing precision fertilisation techniques as well as agroecological and other sustainable approaches; and the use of digital services to help reduce food waste in HICs where such losses are high.
2. Increasing production of healthy and nutritious food without expanding agriculture into new lands and thereby preventing further deforestation. Examples include (but are not limited to): appropriate, efficient and low-emission fertilisation technologies in geographies where fertilisers are under-utilised; improving crop and livestock productivity and resilience to climatic shocks so that farmers improve their yields and incomes where these yields are low (e.g., in many LMICs); and digital services to reduce food loss, particularly in LMICs where post-harvest losses are high.
3. Reducing damage to natural resources, such as soil, water and biodiversity. Examples include (but are not limited to): adoption of agroecological and other sustainable approaches for food production; appropriate use of fertilisers to reduce pollution due to leaching and run-off; various technologies and approaches, such as climate-smart livestock practices for reducing methane emissions from livestock, that also protect natural resources; and changes in dietary preferences, including alternative proteins that have a lower environmental footprint.
4. Reducing emissions, either absolute emissions or emissions intensity, or a combination of both. Examples include (but are not limited to): the adoption of precision fertilisation technologies or low-emission fertilisers; the adoption of technologies and practices that improve livestock efficiency, particularly in LMICs; the adoption of alternative proteins to replace animal-source foods where they are overconsumed; and reducing food loss and waste at all stages of the agricultural value chains.
5. Prioritising the needs and interests of smallholder farmers. Examples include (but are not limited to): providing digital and agricultural climate services (DACS) in the Global South for flood and drought early warning systems; adoption of technologies and approaches suitable for livestock production in the LMICs; or breeding climate-resilient crops for smallholder producers in the Global South.

Figure ES1 provides a conceptual diagram of the four Agriculture Breakthrough principles and five pathways for achieving them.

FIGURE ES1.

Principles and pathways for achieving breakthrough in the agriculture sector



Five Pathways for Achieving Agriculture Breakthrough

PATHWAY 1:
Reduce unsustainable consumption where such consumption has harmful effects on health, climate, and the environment

- Reduce **fertiliser** use by improving NUE in high use areas
- Reduce unsustainable intake of ASF in HIC contexts by partial replacement with **alternative proteins**
- Reduce **food waste**
- Promote sustainable healthy diets with low carbon footprint

PATHWAY 2:
Increase production of sustainable, healthy and nutritious food, particulary in LMICs, without expanding agriculture into new lands

- Increase production through **crop and livestock breeding**
- Increase production through optimal application of low emissions **fertilisers** in areas of underuse
- Increase production through **crop breeding** in areas of low productivity
- Increase production through climate-smart livestock practices and **agroecological** and other sustainable approaches
- Use **digital services** to aid all above

PATHWAY 3:
Reduce damage to natural resources such as soil, water, and biodiversity

- Improve NUE of **fertilisers** allowing less pollutants to leach into water bodies
- Reduce **food waste and loss**
- Use **digital services** to aid all above
- Improve agricultural water management

PATHWAY 4:
Reduce emissions, either absolute emissions or emissions intensity with the ultimate aim of reducing absolute emissions

- Improve NUE and adoption of low emissions **fertilisers**
- Reduce methane emissions from livestock sector; and promote adoption of **alternative proteins**
- Reduce **food waste and loss**
- Use **digital services** to aid all above
- Reduce methane emissions from rice paddy

PATHWAY 5:
Prioritise the needs and interests of smallholder producers

- **Digital services** e.g. climate advisory and indexed based insurance for smallholder producers
- Increase productivity and incomes through **crop and livestock breeding** for smallholder farmers
- Improve resilience of smallholder production systems by adoption of **agroecological** and other sustainable approaches
- Invest in social safety nets for smallholder producers

Supported by international collaborative actions on

Climate finance	Policies regulations and innovations	Metrics indicators and standards	RD&D	Private sector, markets and trade

Note: ASF= animal source foods; HIC = High income countries; NUE= nitrogen use efficiency.
This also provides an Illustrative example of how seven technological areas and approaches map onto different pathways for achieving the breakthrough objectives while adhering to the four breakthrough principles.

This figure is not meant to be a comprehensive mapping of all seven technological areas and approaches across all five pathways, as objectives for many or most of them can be achieved through multiple pathways.
The seven technological areas and approaches covered in this chapter are in bold. New technologies and approaches suggested for inclusion in future reports are in boxes with dotted lines.

The breakthrough technologies

The agriculture chapter in the 2022 Breakthrough Agenda Report (IEA, 2022) identified seven technological areas and approaches that can lead to agricultural breakthroughs. This examines each of these areas and offers insights on the current state of scientific development. It presents solutions that are ready to be implemented on a large scale, as well as technologies and approaches that require further research, development and demonstration (RD&D) before they can be upscaled. The agriculture chapter of the 2023 Breakthrough Agenda Report provides recommendations for international action and collaboration, and it should be read alongside this report as this provides the scientific basis for those recommendations.

The first breakthrough area is reducing emissions from chemical fertilisers. Fertiliser accounted for 10.6% of agricultural emissions and 2.1% of global GHG emissions in 2018. About a third of the emissions related to fertiliser occur during the fertiliser production process, while the remaining two-thirds of the emissions occur after field application (IPCC, 2019; Gao & Cabrera Serrenho, 2023). This report identifies six ways of reducing fertiliser-related emissions during field application and also ways of reducing emissions during fertiliser production processes (e.g., green ammonia).

The second breakthrough technology is alternative proteins. Animal-source foods (ASF) have a high carbon footprint, with livestock and fisheries accounting for 31% of food emissions (Poore & Nemecek, 2018). Livestock production also has a high land and water footprint (Vanham et al., 2023; Heinke et al., 2020) and is considered a leading cause of deforestation (Pendrill et al., 2022). Alternative proteins are a way to reduce consumption of ASF, particularly in HICs, where per capita consumption levels are much higher than global averages. Alternative proteins is a broad term that refers to any protein-rich foods and food products intended to replace those derived from traditional livestock sources, such as meat, eggs, dairy products and fish. This report identifies four types of alternative proteins and identifies barriers and options for their wider uptake.

The third technology area is food loss and waste (FLW). A lifecycle analysis of FLW from the food production and food consumption value chains found that FLW contributed 9.3 billion metric tonnes (MT) of CO^2 equivalent (CO^2e) emissions in 2017 (Zhu et al., 2023). FLW happens throughout the entire value chain and, according to some estimates, almost 30% of food that is produced never reaches consumers (FAO, 2023a), making it a relatively low-hanging fruit for intervention. This report identifies various ways of reducing FLW across the entire value chain.

The fourth technology area is breeding crops and livestock. Breeding crops and livestock that can withstand elevated heat, drought and other climate stresses can help farmers, particularly smallholder farmers in the LMICs, continue to produce food in a changing climate without expanding agricultural land. Crop varieties that use water or fertilisers more efficiently and livestock breeds that emit less methane can help reduce absolute emissions or relative emissions intensity. The report identifies advances in crop and livestock breeding for climate resilience, including various trade-offs for any possible negative impacts of improved breeds on animal health and disease susceptibility.

The fifth area of focus is reducing methane emissions from the livestock sector. Of the 30% emissions from the livestock sector, about 88% come from enteric fermentation in the digestive tracts of ruminant animals (cattle, sheep and goats), released through belching, and the remainder come from manure (FAO, 2022a, c). This report provides a detailed analysis of scale-ready technologies for reducing emissions from both enteric fermentation and manure, and also lists the technologies that are not yet scale-ready but are at various stages of development.

The sixth area is that of agroecological and other sustainable approaches to agricultural production. Guided by a set of principles (e.g., recycling, maintaining biodiversity and enhancing knowledge co-creation), agroecology aims at favouring natural processes that improve resource efficiency, strengthen resilience and secure social equity, while offering both adaptation and mitigation co-benefits to climate risks. This report provides a menu of options for agroecological practices that are context specific and can be co-developed with local farmers and public and private sector actors.

The final technological area is digital services in agriculture, which can help farmers and small agricultural businesses rapidly gain the skills and knowledge they need to adapt to and mitigate climate change while improving food production sustainably, with practical applications in all the above-mentioned technological areas. The report details the various ways in which digital services help smallholder farmers adopt climate-resilient practices.

In the context of these seven technological areas, the report discusses scaling opportunities that require adapting proven technologies to local contexts, investments in local capacity, required inputs and infrastructure, and appropriate institutions and policies. Given the complexity of the sector, trade-offs across the four principles of the breakthrough and the five pathways to achieve them are inevitable. The report documents trade-offs across these dimensions using qualitative expert judgement in each of these technological areas and approaches. The report also identifies a few other technological areas and approaches, such as reducing methane emissions from paddy, improving agricultural water management, and promoting healthy and sustainable diets with a low carbon footprint, which are crucial to the breakthrough agenda and should be included in future reports.

Recommendations for international collaboration

The main objective of the overall Breakthrough Agenda is to strengthen international collaboration to accelerate transitions. This report looks at barriers to implementation in each of the technological areas and makes concrete recommendations for action, with a particular focus on actions that need international collaboration. The following are the five main recommendation groupings:

- **Recommendation 1:** Increased climate finance should be directed to supporting the deployment of agricultural technologies and approaches for which science has generated evidence on effectiveness, including agroecology, reducing food loss and wate, reducing livestock methane emissions, reducing emissions from fertilisers, and crop and livestock breeding.
- **Recommendation 2:** Governments, research institutions, international organisations and the private sector should commit to a long-term process to test, develop evidence and share learning on policy and implementation. This should prioritise the redirecting of subsidies to support agriculture to move towards sustainability and climate resilience, and the facilitation of faster uptake of proven technologies in the sector.
- **Recommendation 3:** Governments, international organisations and research institutes should develop common metrics and indicators to track the adoption of key sustainable agriculture solutions assolutions as well as to monitor the state of natural resources on which agriculture depends.
- **Recommendation 4:** Governments, research organisations and companies should work together to deliver higher levels of investment in agricultural research, development and demonstration, to be maintained over the course of this decade. Priority should be given to innovations that can reduce methane emissions from livestock, make alternative proteins a reliable and affordable option, increase the resilience of crops, and advance uptake of digital services by farmers.
- **Recommendation 5:** Governments should begin strategic dialogues on how to ensure international trade facilitates, and does not obstruct, the transition to sustainable agriculture. In addition to addressing the agricultural commodities that contribute disproportionately to deforestation, early priority should be given to agreeing standards, labels and regulations for alternative proteins, low emission fertilisers, and products of agroecological and other sustainable approaches, and to developing intellectual property frameworks that promote access to resilient and low emission crop and livestock varieties. This should be complemented with international sharing of best practice on mobilising private investment and engaging consumers.

1 Introduction

Core authors: **Aditi Mukherji, Loraine Ronchi**

Climate-resilient, sustainable agriculture is the most attractive and widely adopted option for farmers everywhere by 2030.

Agriculture Breakthrough goal

The world is 1.1°C warmer than pre-industrial times due to human-caused greenhouse gas (GHG) emissions (IPCC, 2023a). In total, 76% of GHG emissions come from electricity, heat, transport and industrial processes, and the rest from the agriculture, food and other land use (AFOLU) sector, which includes emissions from food production (agriculture), forests and land use (IPCC, 2023b). However, when the entire food value chain, from production, processing, distribution and consumption, and food loss and waste are included, the emissions from the agrifood sector amount to one-third of total GHG emissions (Crippa et al., 2021; Poore & Nemecek, 2018; Rosenzweig et al., 2020; see Figure 1.1). In 2015, food-system emissions amounted to 18 Gt CO^2 equivalent (CO^2e) per year globally, representing 34% of total GHG emissions (Crippa et al., 2021). The impacts of climate change are felt globally, with the agriculture sector being particularly vulnerable to climate change. Losses and damages are already occurring throughout the agricultural value chains due to extreme weather events like high temperatures, droughts and floods. Small-scale farmers in the Global South are especially at risk, and current efforts to adapt to climate change are not sufficient (IPCC, 2023b). To meet the Paris Agreement goals, immediate, rapid and deep emission reductions are needed in all sectors, including the agriculture sector and entire food systems. However, such emission reductions need to be done without threatening food production, and hence transitions need to be equitable and just. In the mean time, it is also clear that without a reduction in agricultural emissions, even if all other sectors meet their emission reduction targets, global warming will still increase well beyond the 1.5°C limit and nearly overshoot the 2°C limit (Clark et al., 2020; IPCC, 2023a). Emissions reduction in this sector requires transformative and deep changes (breakthroughs), which would involve putting agriculture on a low emissions pathway while also delivering food and nutrition security, but without further damaging land, water and other natural resources in the process of food production. However, no silver bullet or one size fits all type of solution exists for such equitable and just transitions in the agrifood sector, for several reasons.

FIGURE 1. 1

GHG emissions from food systems

How much of global greenhouse gas emissions come from the food system

Shown is the comparison of two leading estimates of global greenhouse gas emissions from the food system. Most studies estimate that food and agriculture is responsible for 25% to 35% of global greenhouse gas emissions

Poor and Nemecek (2018)
13.6 billion tonnes CO^2e from food
That's 26% of global GHG emissions
(Increases to 33% with non-food agricultural products)

Crippa et al. (2021)
17.9 billion tonnes CO^2e from food*
That's 34% of global GHG emissions
(*som non-food agricultural products included)

Source: Our World in Data

First, agriculture, a major contributor to global GHG emissions, is also highly exposed to climate change. Over the past 50 years, global agricultural productivity growth has slowed due to climate change, causing losses and damages in sectors like agriculture, forestry and fishery, especially in low- and middle-income countries (LMICs) in the Global South (IPCC, 2022b). These impacts are further projected to grow in a warmer world (Jägermeyr et al., 2021). Climate change has and will increase food insecurity and vulnerability among already vulnerable populations (Hasegawa et al., 2021). Apart from climate change related impacts, current ways of producing, distributing and consuming food have left millions under-nourished, malnourished and hungry, with recent estimates saying that between 702 to 828 million people faced hunger in 2021 (FAO et al., 2022). Many current agricultural practices also cause damage to land, water and biodiversity, thereby reducing the benefits that can be derived from nature. This calls for a just and equitable transition in agrifood systems (Tribaldos & Kortetmäki, 2022), one that keeps the interests of the poor and of vulnerable producers and consumers at its heart.

Second, some recent studies, using modelling approaches and standard carbon prices, have shown that stringent mitigation actions in the agriculture sector, when implemented across the board without contextualising them, can compromise food security and increase hunger. For example, Hasegawa et al. (2018) found that climate mitigation policies implemented by 2050 would have a more significant adverse effect on global hunger and food consumption than direct impacts of climate change per se. Hasegawa et al. (2018) concluded that land-based mitigation measures, such as energy crop expansion, reduction of non-CO^2 emissions during food production, and afforestation, could lead to reduced calorie availability, increased vulnerability to hunger and higher agricultural commodity prices. This points to the need to carefully select mitigation interventions in the agriculture and food sector that do not compromise food security, particularly for the poorest. Other studies (such as WRI, 2019) show that such options for mitigation interventions exist, but need careful selection.

Third, in contrast to the energy and transport sectors, where technologies and approaches like clean electricity, energy efficiency and low-carbon transport are relatively mature due to early investments and are almost universally applicable (although implementation barriers like lack of finance for the Global South remain), technologies and approaches available for reducing GHG emissions in agriculture are highly context-specific, and not always scale ready, and therefore require a far greater degree of due diligence before implementation. In other words, there are no universally applicable technological silver bullets in this sector, although a wide variety of context-specific options exist. As a result, a full set of innovations in practices, technologies, policies and financing, across various subcomponents of agricultural production, processing, distribution, consumption, and loss and waste throughout the value chain, are needed, to transition to climate-resilient and sustainable agriculture.

This report highlights the complexities of Agricultural Breakthrough and the need for transforming food systems to be productive, climate-resilient, sustainable and equitable while reducing GHG emissions from the sector. To achieve the Agriculture Breakthrough, the agriculture chapter in the 2022 Breakthrough Agenda Report (IEA, 2022) had identified four principles, namely: (1) sustainably increasing agricultural productivity and incomes; (2) reducing GHG emissions; (3) safeguarding soil, water resources and natural ecosystems, and (4) adapting to climate change. Given the diversity and complexity of the agrifood sector, this report considers the different geographical and socioeconomic contexts in which these four principles apply and accordingly qualifies them further. Figure 1.2 depicts these four modified principles, which are:

- Agricultural productivity and incomes must increase sustainably, particularly in LMICs, where current productivity is low, in order to achieve food and nutrition security, and healthy and sustainable diets for all.
- The sector must reduce GHG emissions and, depending on socioeconomic conditions and technologies and approaches, these can be either reductions in emissions intensity, or absolute emissions reductions, or both, with the ultimate aim of reducing absolute emissions.
- Soil, water and natural ecosystems must be safeguarded across all geographies, including through a focus on healthy ecosystems.
- The sector must adapt and build resilience to climate change, including through approaches that promote inclusion and social safety nets for the poor and for vulnerable smallholder producers in the Global South.

Achieving breakthrough in the agrifood sector requires simultaneous actions across various subsectors in the agriculture sector, including identification of win–win solutions, such as halting deforestation by shifting to healthy sustainable and less meat-based diets, and reducing food waste and loss. Overall, the fragmented nature of the agriculture sector requires multiple game-changing innovations to be implemented simultaneously across different production systems.

Literature suggests that it is possible to achieve net zero emissions in food systems by 2050 without relying on carbon dioxide removals and offsets but does not explicitly say if that net zero can be achieved without compromising food and nutrition security. Achieving net zero would involve large-scale adoption of low-emission agricultural practices, such agroecological and other sustainable approaches. Realising carbon sequestration potential of low-emission practices could reduce emissions further. Additional emissions reductions would involve demand-side changes, such as shifting diets from meat-based to plant-based, particularly in high-income countries (HICs), and adoption of technologies that are not yet mature (e.g., cost-effective production of green ammonia) but expected to be so in a decade or so (Costa et al., 2022). However, what is not clear is how much of this technical potential can translate to economic potential for emissions reduction, as economically feasible emission reductions are several orders lower than technical potential (Rosenzweig et al., 2020). Notably, climate finance for agricultural innovation has been significantly lower than that for energy and other sectors that benefited from early-stage subsidy financing, triggering innovations.

However, there are available technologies that can make emissions reduction in food systems possible, although the potential impacts of those technologies on food security needs to be examined. For example, a study by Gao & Cabrera Serrenho (2023) shows that interventions at farm and production stage can reduce emissions from synthetic nitrogen fertilisers by up to 84% by 2050. A shift from animal-based to plant-based diets in HICs can potentially cut annual agricultural production emissions as well as sequester carbon (Sun et al., 2022). Additionally, increasing crop and animal productivity and reducing food loss and waste can bridge the nutritional gap but with lower emissions than business-as-usual production patterns, showing that examples of win–win actions across the broad spectrum of food systems is possible (Geyik et al., 2023) when trade-offs and synergies are carefully considered (Snapp et al., 2023).

So, while there are available technologies and approaches that can reduce GHG emissions from the food systems, those are not always readily known or understood as scalable by public and private sector investors, given their context specificity. The purpose of this report is to fill that gap in knowledge. We use the term technological areas and approaches throughout to describe these innovations in practices, technologies, policies and financing. We look at seven technological areas and approaches that were prioritised in the Agriculture Breakthrough chapter of 2022 (IEA, 2022). The chapter had set the overall goal of Agriculture Breakthrough, as "climate-resilient, sustainable agriculture is the most attractive and widely adopted option for farmers everywhere by 2030", and had stipulated four guiding principles for achieving this goal, which this report has modified somewhat to account for various socioeconomic and geographical diversity within this sector. The figure also lists ways of achieving those breakthroughs via five pathways as follows:

1. Reducing unsustainable consumption where such consumption has harmful effects on health, climate and the environment. Examples include (but are not limited to): alternative proteins to address high meat consumption in HICs; reducing the use of fertilisers and improving nitrogen use efficiency (NUE) in regions of excess application by implementing precision fertilisation techniques, as well as agroecological and other sustainable approaches; and the use of digital services to help reduce food waste in HICs where such losses are high.
2. Increasing production of healthy and nutritious food without expanding agriculture into new lands and thereby preventing further deforestation. Examples include (but are not limited to): appropriate, efficient and low-emission fertilisation technologies in geographies where fertilisers are under-utilised; improving crop and livestock productivity and resilience to climatic shocks so that farmers improve their yields and incomes where these yields are low (e.g., in many LMICs); increase livestock production

through climate-smart practices that also reduce methane emissions, again in LMIC contexts; and digital services to reduce food loss, particularly in LMICs where post-harvest losses are high.

3. Reducing damage to natural resources, such as soil, water and biodiversity. Examples include (but are not limited to): adoption of agroecological and other sustainable approaches for food production; appropriate use of fertilisers by improving NUE to reduce pollution due to leaching and run-off; various technologies and approaches, such as climate-smart livestock practices for reducing methane emissions from livestock that also protect natural resources; and changes in dietary preferences, including alternative proteins that have a lower environmental footprint.
4. Reducing emissions, either absolute emissions or emissions intensity, or a combination of both. Examples include (but are not limited to): the adoption of precision fertilisation technologies or low-emission fertilisers; the adoption of technologies and practices that improve livestock efficiency, particularly in LMICs; the adoption of alternative proteins to replace animal-source foods where they are overconsumed; or reducing food loss and waste at all stages of the agricultural value chains.
5. Prioritising the needs and interest of smallholder farmers. Examples include (but are not limited to): providing digital agricultural climate services (DACS) in the Global South for flood and drought early warning systems; adoption of technologies and approaches suitable for livestock production in the LMICs; or breeding climate-resilient crops for smallholder producers in the Global South.

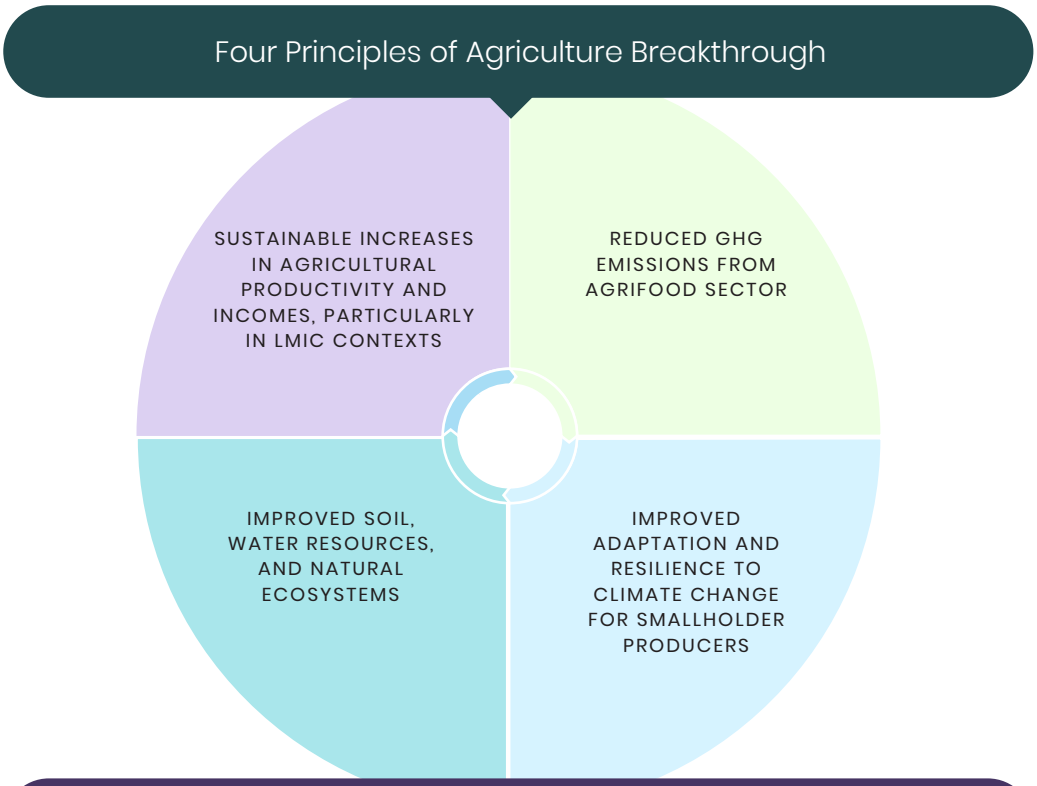
The seven technological areas/approaches identified in 2022 were:

- Reduced emissions from fertilisers
- Alternative proteins
- Reduced food loss and waste
- Crop and livestock breeding
- Reduced methane emissions from livestock
- Agroecology and other sustainable approaches
- Digital agricultural and climate services (DACS)

Figure 1.2 shows how these four principles, five pathways and seven technological areas/approaches (indicated by the underlined text) will contribute to the overall objective of the Agricultural Breakthrough agenda. The four (modified) principles are the desired outcomes of the agricultural breakthrough, the five pathways are ways through which these desired outcomes can be achieved, and the seven technological areas and approaches are concrete actions that need to be taken to achieve the desired outcomes. The technologies and approaches mentioned in dotted boxes (e.g., promote sustainable healthy diets with low carbon footprint; improve agricultural water management; reduce methane emissions from rice paddy; and invest in social safety nets for smallholder producers) are not included in this report, but are important areas for inclusion in future breakthrough reports on agriculture. The figure also shows the five major groupings of recommendations for international collaborative actions that this report makes.

FIGURE 1.2

Principles and pathways for achieving breakthrough in the agriculture sector



Five Pathways for Achieving Agriculture Breakthrough

PATHWAY 1:
Reduce unsustainable consumption where such consumption has harmful effects on health, climate, and the environment

- Reduce **fertiliser** use by improving NUE in high use areas
- Reduce unsustainable intake of ASF in HIC contexts by partial replacement with **alternative proteins**
- Reduce **food waste**
- Promote sustainable healthy diets with low carbon footprint

PATHWAY 2:
Increase production of sustainable, healthy and nutritious food, particulary in LMICs, without expanding agriculture into new lands

- Increase production through **crop and livestock breeding**
- Increase production through optimal application of low emissions **fertilisers** in areas of underuse
- Increase production through **crop breeding** in areas of low productivity
- Increase production through climate-smart livestock practices and **agroecological** and other sustainable approaches
- Use **digital services** to aid all above

PATHWAY 3:
Reduce damage to natural resources such as soil, water, and biodiversity

- Improve NUE of **fertilisers** allowing less pollutants to leach into water bodies
- Reduce **food waste and loss**
- Use **digital services** to aid all above
- Improve agricultural water management

PATHWAY 4:
Reduce emissions, either absolute emissions or emissions intensity with the ultimate aim of reducing absolute emissions

- Improve NUE and adoption of low emissions **fertilisers**
- Reduce methane emissions from livestock sector; and promote adoption of **alternative proteins**
- Reduce **food waste and loss**
- Use **digital services** to aid all above
- Reduce methane emissions from rice paddy

PATHWAY 5:
Prioritise the needs and interests of smallholder producers

- **Digital services** e.g. climate advisory and indexed based insurance for smallholder producers
- Increase productivity and incomes through **crop and livestock breeding** for smallholder farmers
- Improve resilience of smallholder production systems by adoption of **agroecological** and other sustainable approaches
- Invest in social safety nets for smallholder producers

Supported by international collaborative actions on

Climate finance	Policies regulations and innovations	Metrics indicators and standards	RD&D	Private sector, markets and trade

Note: ASF= animal source foods; HIC = High income countries; NUE= nitrogen use efficiency.
This also provides an Illustrative example of how seven technological areas and approaches map onto different pathways for achieving the breakthrough objectives while adhering to the four breakthrough principles.
This figure is not meant to be a comprehensive mapping of all seven technological areas and approaches across all five pathways, as objectives for many or most of them can be achieved through multiple pathways.
The seven technological areas and approaches covered in this chapter are in bold. New technologies and approaches suggested for inclusion in future reports are in boxes with dotted lines.

The rest of this report is organised as follows. Sections 2 to 7 look at these seven technological areas in detail, by listing all the innovations and approaches that exist today and are ready to be scaled up for implementation. In doing so, the authors provide a qualitative assessment (based on expert judgement) of those innovations across the four principles of breakthrough. We also look at barriers to implementation and make concrete recommendations for action, with a particular focus on actions that need international collaborations. Our recommendations for collaborative international actions focus on: climate finance; policies, regulations and innovations; metrics, indicators and standards, research, development and demonstration (RD&D); and action by private sectors and markets (see Section 9 for a summary of all recommendations).

Field visit to climate smart villages in Ludhiana, India, in September 2015.
Leo Sebastian (IRRI-CCAFS)

2 Reduced emissions from fertilisers

Core authors: **Tek Sapkota, Aditi Mukherji**
Contributing authors: **Job Kihara, Oscar Ortiz**

KEY HIGHLIGHTS

- Chemical fertilisers play a critical role in ensuring agricultural production and food security.
- Both over-fertilisation and under-fertilisation across global croplands have resulted in numerous environmental issues, including climate change and soil degradation.
- Various technologies can be adopted (during both the production process and the field application of fertilisers) to sustainably increase agriculture production and income, build resilience to climate change and safeguard natural resources while reducing GHG emissions.
- There is a need for greater funding, enhanced global collaboration and partnerships for knowledge generation and exchange, improved data infrastructure, standardisation of market regulations/standards and redirection of subsidies towards these low-emission technologies.

2.1 The context

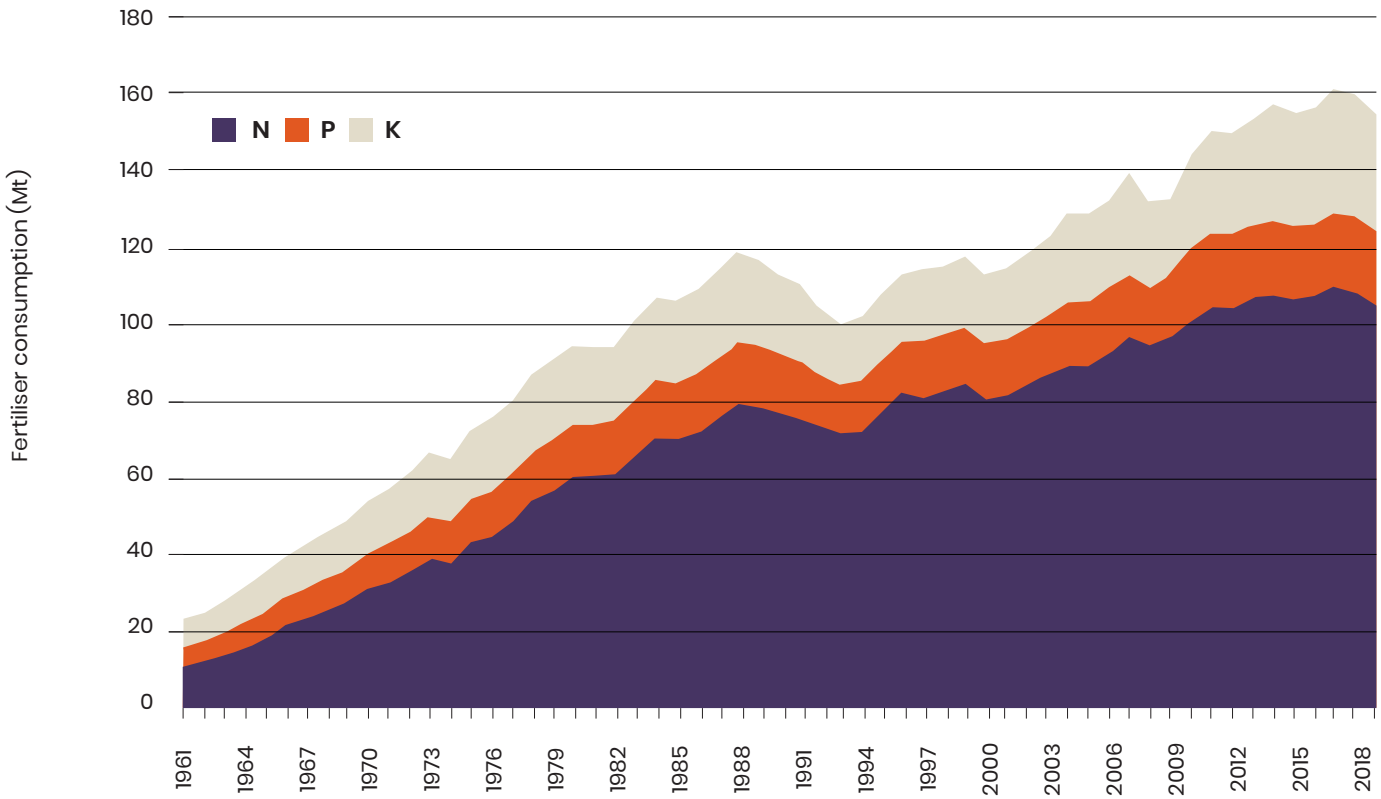
Chemical fertilisers have been an important part of global agricultural crop productivity since the 1960s, with global use increasing from 16 million tonnes in 1960 to 186 million tonnes in 2020 (FAO, n.d.; Figure 2.1). FAOSTAT data show that global use of total inorganic fertilisers for agriculture has, however, slowed since 2000 compared with the 1961–1990 period. Fertiliser use is uneven, with some regions applying excess fertilisers and others experiencing severe shortages (Mueller et al., 2012; Mueller et

al., 2014: Figure 2; Snapp et al., 2023). Excessive and inefficient use of fertiliser for crop production is associated with reduced nitrogen use efficiency (NUE), and also increases cost of production (low profitability), reduces agricultural productivity and leads to GHG emissions, primarily of nitrous oxide (N_2O) (Maaz et al., 2021), which has 300 times more warming potential than CO^2. Globally, NUE is low, with half of the nitrogen applied to crops currently being lost to the environment (Zhang et al., 2015) and excess nitrogen not used by plants is a leading cause of pollution of surface water bodies.

Synthetic nitrogen fertiliser accounted for 1.13 Gt CO^2e of emissions in 2018, which represented 10.6% of agricultural emissions and 2.1% of global GHG emissions. Most of the emissions from fertilisers are composed of N_2O: N_2O is responsible for 5% of today's global warming and over 60% is emitted from fertiliser production and use (IPCC, 2019; 2022a; Gao & Cabrera Serrenho, 2023). The top four emitters together – China, India, USA and the European Union (EU) – accounted for 62% of the total, although a large decrease in total fertiliser use in China has been observed since 2015, and fertiliser use in the USA and EU has remained stable, counteracting growth elsewhere (Menegat et al., 2022).

FIGURE 2.1

Fertiliser used by nutrient, 1961–2020.



Source: FAO several years; Ritchie et al., 2022
Note: Fertiliser use in agriculture sector, which includes use for crops, livestock, forestry, fisheries and aquaculture.

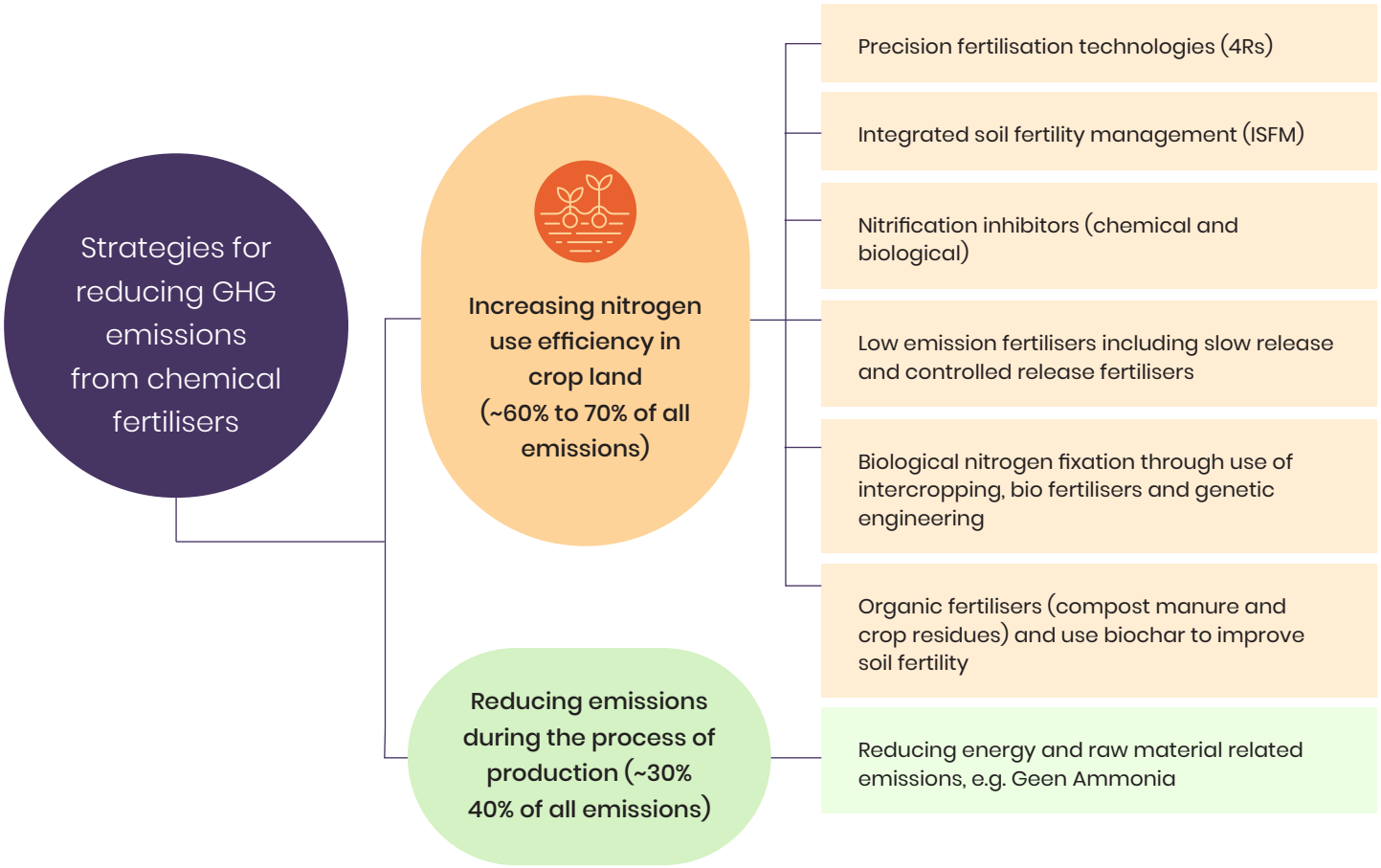
To sustain global food production and reduce GHG emissions simultaneously, it is important to reduce global inequalities of agricultural fertiliser use and promote pathways to reduce over-use of chemical fertilisers while also promoting appropriate use of various forms of fertiliser for optimal plant nutrition in areas where fertilisers are under-used. (Ren et al., 2023). Indeed, opportunities exist to reduce fertiliser application in high-application areas without compromising food production, while increasing access and use of fertiliser in low-application areas such as sub-Saharan Africa for enhancing food security (Bonilla-Cedrez et al., 2021). The overall policy goal in this space is to provide optimal plant nutrition while reducing environmental damages.

2.2 Strategies and technologies for reducing emissions from fertilisers

Emissions related to fertiliser occur during the fertiliser production stage (between 30% to 40% according to estimates), while the remaining 60% to 70% of emissions occur after field application (Gao & Cabrera Serrenho, 2023; Menegat et al., 2022). It is possible to reduce GHG arising from chemical fertilisers by up to 84% by 2050 by using a combination of options with different levels of technology and scaling-readiness (Gao & Cabrera Serrenho, 2023; Figure 2.2).

Crop harvesting in an on-farm, farmer-managed experiment looking at new wheat varieties, planting dates, and nitrogen levels.
Tim Krupnik (CIMMYT)

FIGURE 2.2 **Strategies for reducing emissions from chemical fertilisers**



Source: Authors

2.2.1 Measures to increase NUE in crop land

2.2.1.1 Precision fertilisation technologies

Precision fertilisation technology, which involves application of the 4Rs – the right fertiliser, at the right time, in the right amount and in the right place – to fulfil the individual demands of crops (also called 4Rs), can reduce fertiliser application rates, boost nutrient usage efficiency and improve environmental sustainability (Burns et al., 2010; Snyder, 2017). There are various available and tested technologies for delivering precise fertilisation in the field, as described below.

- Variable rate fertilisation (VRF) is a technology that varies the quantity of fertiliser applied within the field based on soil's nutrition supplying capacity and the plants' nutrient requirements. VRF has been proven in studies to significantly reduce nitrogen consumption, resulting in lower GHG emissions while maintaining or increasing crop yields (Kazlauskas et al., 2021; King et al., 2022), and improving soil and water quality by minimising fertiliser leaching and run-off (Norlida et al., 2021).
- Site-specific nutrient management (SSNM) dynamically adjusts field fertiliser use to optimally fill the deficit between the nutrient needs of the crop and the nutrient supply from naturally occurring sources such as soil, crop residues, organic inputs and irrigation water. SSNM aims to recommend nutrients at optimal rates and times to achieve high profit for farmers, with high efficiency of nutrient use by crops across the spatial and temporal scales, thereby reducing fertiliser-induced GHG emissions (Sapkota et al., 2014; Nkebiwe et al., 2016).
- Precision irrigation and fertilisation techniques, such as drip irrigation and fertigation, have emerged as useful solutions for lowering fertiliser emissions (Azad et al., 2021; Pibars et al., 2022). Technologies such as soil sensors, remote sensing and geographic information systems (GIS) and big data (Gao & Cabrera Serrenho, 2023; Gao & Li, 2022) are increasingly being utilised to precisely calculate crop nutrient requirements and apply fertilisers accordingly. These systems together deliver water and nutrients directly to the root zone, reducing nutrient leaching and evaporation and increasing crop output and water efficiency (Sidhu et al., 2019).
- Nano-fertilisers are a potential breakthrough for lowering fertiliser emissions, as they are intended to improve crop nutrient absorption (Toksha et al., 2021; Su et al., 2022; Kumar et al., 2022). Some studies have yielded promising results in terms of improving plant growth and reducing fertiliser use, but there are also concerns about nanoparticle accumulation in soils and ecosystems over time (Zulfiqar et al., 2019). Further, nano-formulations need to be improved for widescale adoption to improve economic and environmental benefits (Su et al., 2022).
- Decision support systems, tools, techniques and machineries help make decisions on precision nitrogen fertilisation for each field. These include machineries to drill fertilisers equipped with global positioning system (GPS) receivers to map soil properties and yield potential, and data analysers to determine optimal fertiliser rates (Golicz et al., 2019) are used by (or accessible to) large-scale producers and farmers in the developed world. Precision nutrient application can also be adopted in smallholder production systems using handheld sensors or decision support systems without the need for expensive machineries or soil testing systems (Lapidus et al., 2022; Maaz et al., 2021).

Local recommendations tailored to specific areas are important to improve fertiliser use efficiency, especially across the range of smallholder farmers who cannot currently implement precision fertilisation. Through applying such recommendations, 21 million farmers in China with cumulative cropped land of 38 million hectares across 10 years reduced nitrogen fertiliser use (by up to 18%) and resulting emissions (by 19%), and still increased production by up to 11% (Cui et al., 2018). Evidence from Madagascar shows that phosphorus dipping of rice seedlings is an effective technique to improve both applied phosphorus use efficiency and rice yield in smallholder farms (Oo et al., 2020). Many countries, especially developing ones, lack such site-specific recommendations.

2.2.1.2 Integrated soil fertility management

Integrated Soil Fertility Management (ISFM) is an approach that ensures efficient recycling of nutrients through organic resources and maintenance of soil organic carbon for healthy soil (Vanlauwe et al., 2010). The 4R principles of nutrient stewardship fit well within the ISFM approach, as both focus on ensuring nutrients are used efficiently. ISFM entails using the right varieties and combining organic and chemical fertilisers for increased nutrient use efficiency. It also considers that factors such as soil acidity and rooting depth, which impede crop growth and nutrient use, should be addressed. Snapp et al. (2023) argue that ISFM and other strategies depend on the current situation of fertiliser use, which defines the possible transition pathways to more sustainable agriculture and lower GHG emissions. Agroecological and other sustainable approaches to soil fertility management (e.g., organic fertilisers and reduced tillage) can lead to long-term improvements in soil organic content, but cannot reduce nitrous oxide emissions under all pedoclimatic and farming conditions (Grados et al., 2022).

2.2.1.3 Nitrification inhibitors

Nitrification is the bacterial process of converting ammonium (NH4+) into nitrate (NO3–) in soil. Excessive nitrification can lead to nutrient loss through leaching, run-off and emissions (Su et al., 2022; Wu et al., 2021; Gilsanz et al., 2016). Nitrification inhibitors work by inhibiting the activity of nitrifying bacteria to slow down the process of nitrification and enable gradual release of NO3– into the soil for plant uptake. Synthetic nitrification inhibitors such as dicyandiamide (DCD), 3,4-dimethylpyrazole phosphate (DMPP) and nitrapyrin can be administered to the soil alone or in conjunction with fertilisers and can increase crop yields, improve soil organic carbon sequestration rate and mitigate N_2O emissions (Gao & Li, 2022; D. Dong et al., 2022). Although nitrification inhibitors effectively reduce direct emissions of N_2O and leaching of (NO3–), there is some evidence that they lead to an increase in ammonia (NH_3) volatilisation and, consequently, indirect emissions of N_2O, which can undermine its overall effectiveness (Lam et al., 2017)

Biological Nitrification inhibitors (BNI) include a range of naturally released compounds – i.e., from micro-organisms, organic materials or plant root exudates – that also possess nitrification inhibition properties. By including plants with BNI properties in the cropping systems or transferring BNI properties to the commercial crop of interest, there is huge potential to increase NUE and improve crop yield (Leon et al., 2021; Subbarao et al., 2021).

2.2.1.4 Low-emission fertilisers

Low-emission fertilisers enhance fertiliser efficiency while lowering emissions of N_2O. Low-emissions fertilisers, such as controlled-release fertilisers and slow-release fertilisers have been developed and tested in various countries. Controlled-release or slow-release fertilisers are a form of fertiliser that releases nutrients gradually and in controlled quantities over a period based on plant demand to ensure efficient uptake by plants and minimise loss (Ni et al., 2011). Controlled-release fertilisers are covered with a polymer membrane that regulates nutrient delivery depending on soil moisture and temperature (Mikula et al., 2020; Lawrencia et al., 2021). They are designed to optimise nutrient uptake and make more efficient use of nutrients, leading to improved crop yield (Zhu et al., 2020) and reduced fertiliser losses including emissions (Zhang et al., 2020).

Compost, manure and sewage sludge are examples of organic slow-release fertilisers (Rashid et al., 2021) and coated fertilisers such as sulphur-coated urea, neem-coated urea and polymer-coated urea (Mehmood et al., 2019) are examples of synthetic slow-release fertilisers. Availability of natural organic fertilisers in sufficient quantities in specific locations remains a challenge.

2.2.1.5 Biological nitrogen fixation

Biological nitrogen fixation (BNF) is a naturally occurring process to convert atmospheric nitrogen into plant-usable form. Legumes in crop rotation and intercropping contribute nitrogen through BNF, improve soil quality and increase yields (Lötjönen & Ollikainen, 2017; Senbayram et al., 2015). The biologically fixed nitrogen reduces the need for high chemical nitrogen fertiliser applications (MacLaren et al., 2022). Specific biofertilisers containing more effective nitrogen-fixing bacteria than native strains can be used to increase legume BNF. Besides this, genetic engineering, which entails inserting genes from nitrogen-fixing bacteria into crops that do not fix nitrogen, has the potential to significantly reduce the need for chemical fertilisers, but research on this is still in its initial stages, and there are regulatory and ethical concerns (Olivares et al., 2013; Boddey et al., 2015; Pankievicz et al., 2019; Dent & Cocking, 2017; Nag et al., 2020; Dong & Lin, 2020).

2.2.1.6 Organic fertilisers and biochar

Organic fertilisers such as manure and compost, where available in sufficient quantities, can be low-emission alternatives to chemical fertilisers. However, this is often not the case, especially for the majority of smallholder farmers. Combining these organic resources with chemical fertilisers is a more feasible alternative. Whether alone or in combinations, particularly in fertiliser-deficient areas, organic resources modify soil carbon availability and act as a nutrition source for soil microbes (Charles et al., 2017). Carbon sequestration capacity of organic manure and compost can increase soil organic carbon (Spaccini, 2019). However, a meta review of lifecycle studies shows that manure emits 1.9 times more GHGs than an average synthetic fertiliser per unit of nitrogen (Gao & Serrenho, 2023). Other studies also suggest that increased soil N_2O emissions and CH_4 emissions can offset the benefit of increasing soil organic carbon stocks as GHG sinks (Zhou et al., 2017).

Crop residues recycle nutrients and organic matter back to the soil. When applied together with legume cover crops and chemical fertilisers, the residues reduce nutrient losses through an initial immobilisation and slow release during the growing season. However, more research is needed to determine the real carbon sequestration and nutrient source potential in the Global South (Ghimire et al., 2017; Harindintwali et al., 2020). New emerging evidence suggests that it is possible to incorporate fungivorous mites through application of coconut husks as a soil conditioner, which then substantially decreases the N_2O emissions from soil, as mites rapidly consume fungal N_2O producers in soil (Shen et al., 2021).

Biochar is a form of charcoal produced locally by heating organic materials such as agricultural waste, forestry residue and animal dung in a low-oxygen atmosphere (Mehmood et al., 2017; Gabhane et al., 2020). Biochar is primarily integrated into soils to stimulate soil microbial activity and thus nutrient availability, particularly in depleted soils. It can help to reduce GHG emissions by sequestering carbon in the soil, as well as enhancing soil structure and increasing water-holding capacity (Shakoor et al., 2021), resulting in less irrigation and higher agricultural yields (Edeh et al., 2020), while some studies also reported that biochar reduces leaching-out of nitrogen and phosphorus into water (Kuo et al., 2020). Biochar production via biomass pyrolysis is a carbon dioxide removal technology, but uptake requires acceleration through cost reductions and co-benefits (Buss et al., 2022). Biochar systems can reduce emissions by 3.4–6.3 $PgCO^2e$, but trade-offs exist between making and sequestering biochar and energy efficiency (Lehmann et al., 2021). A meta-analysis of 194 studies reveals that biochar has a positive impact on microbial biomass, but its effects on microbial diversity vary (Li et al., 2020). Biochar is not yet readily available.

2.2.2 Measures to reduce emissions from fertiliser production processes

Low-emission fertiliser manufacturing technologies are essential for lowering GHG emissions and decreasing the environmental effects of fertiliser production (Madanhire et al., 2014). Green ammonia is one example of a low-emission fertiliser manufacturing technique, created by utilising renewable energy sources such as wind or solar power to fuel the traditional Haber–Bosch process (Zhang et al., 2020; Ornes, 2021). Carbon capture and storage (CCS) technology is also used in fertiliser manufacturing facilities, even though process CO^2e is an inherent by-product of the production process, which cannot be captured by CCS (Ray & Marriot, 2021). Other low-emission fertiliser production processes have been in use for many years, such as the utilisation of waste materials as feedstock for fertiliser manufacturing. Where these waste products are reused, the emissions connected with trash disposal are minimised, as is the demand for synthetic fertilisers (Chojnacka et al., 2020; Shak et al., 2013).

CASE STUDY 2.1

Digital Nutrient Management Tools in India

India consumes 14% of the total fertiliser used globally, but its NUE is one of the lowest in the world, mainly because of outdated fertiliser recommendations. Better nutrient management using digital tools, such as the Nutrient Expert decision support tool, can increase NUE, boost crop productivity and increase farmers' income while reducing chemical fertiliser use and GHG emissions. Nutrient Expert is an easy-to-use, interactive, computer-based tool that captures the spatial and temporal variability of nutrient status in soil and provides precise nutrient recommendations to smallholder farmers. An experimental study found that Nutrient Expert-based recommendations lowered global warming potential by 12–20% in wheat and by around 2.5% in rice, compared with conventional farming fertilisation practices (Sapkota et al., 2021). Over 80% of farmers were also able to increase their crop yields and incomes using the tool. A scenario analysis reveals that adoption of such practices across all rice and wheat fields in India would provide 14 million tonnes (Mt) of extra grain with 1.44 Mt less nitrogen consumption, which would result in 5.34 Mt less CO^2e emissions, which is equivalent to taking 1.2 million cars off the road every year. Systematic efforts in knowledge sharing, capacity building and incentivisation through appropriate policy measures (e.g., digital extension, repurposing subsidies) and incentive mechanisms (payment for ecosystem services, price premium, responsible sourcing, corporate social responsibility, etc.) help large-scale adoption of such innovative fertiliser management approaches for achieving food security and GHG emission reduction goals.

2.3 Metrics for measuring progress

Universally accepted targets for absolute emissions reductions from fertiliser use do not exist. According to Gliessman (2016) and the International Fertilizer Association (IFA) (2022), fertiliser-induced field emissions amounted to 717 Mt CO^2e in 2019. Gao and Cabrera Serrenho (2023) used a modelling approach to show that it is possible to reduce GHG emissions from fertiliser application by 84% by 2050, provided all technologically available and viable methods are used in conjunction. According to the IPCC (2023a), the global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot require 43% [34%–60% range] reductions in emissions from 2019 levels. Using these targets, global emissions from fertiliser could approach 400 Mt CO^2e and 115 Mt CO^2e by 2030 and 2050 respectively, down from 717 Mt CO^2e in 2019. The IFA (2022) has proposed improving NUE from 50% globally in 2019 to 70% globally by 2040, which will mean GHG emissions from fertiliser use of between 300 Mt CO^2e and 500 Mt CO^2e by 2040. The Food and Agriculture Organization (FAO) and Intergovernmental Technical Panel on Soils (ITPS) (2018), based on the "4 per 1000" initiative, have set a target of achieving global soil organic carbon stocks for topsoil of 713 peta-grams in 2030, up from 680 peta-grams in 2018 (Table 2.1).

A farmer from Rajbari District, Bangaldesh used seeder fertilizer drills (SFD) to plant wheat. Previously this was done manually. SFD resulted in a better harvest.
Ranak Martin / CGIAR

TABLE 2.1 **Metrics for measuring progress in reducing emissions from fertilisers**

Dimensions of breakthrough	Indicators with baseline and target values
Sustainably increases agricultural productivity and incomes	No targets exist on sustainably increasing agricultural productivity and incomes in relation to emissions reductions from fertilisers. There is, however, the Sustainable Nitrogen Management Index (SNMI), a one-dimensional ranking score that combines two efficiency measures in crop production – namely, NUE and land use efficiency (crop yield). However, targets for the same do not exist. Source: *https://essopenarchive.org/doi/full/10.1002/essoar.10501111.1* *https://dashboards.sdgindex.org/map/indicators/sustainable-nitrogen-management-index*
Reduces GHG emissions	**Indicator 1: Emissions from fertilisers** **Baseline (2019):** 717 Mt CO^2e (fertiliser-induced field emissions (IFA, 2022) **Target (2030):** ~400 Mt CO^2e (assuming 43% reduction target by 2030 to keep within 1.5°C) (IPCC, 2023a) **Target (2050):** ~115 Mt CO^2e (assuming 84% reduction potential by 2050 when all available technologies are used in conjunction) (Gao & Cabrera Serrenho, 2023) **Indicator 2: Improving NUE** **Baseline (2019):** 50% globally (IFA, 2022) Target **(2040):** 70% (resulting in 220–420 Mt CO^2e saving by reducing N_2O and CO^2e emissions; leading to 500 Mt CO^2e to 300 Mt CO^2e fertiliser-induced field emissions by 2040 assuming 717 Mt CO^2e baseline in 2019 (IFA, 2022)
Safeguards soil, water resources and natural ecosystems	**Indicator 1: Increase soil carbon content** Baseline (2018): Global soil organic carbon stock for topsoil (0 to 30 cm) is 680 peta-grams Target (2030): 713 peta-grams Assuming 4‰ increase based on "4 per 1000" initiative (FAO and ITPS, 2018) Target (2030): Reduce nitrogen pollution by 50% by 2030 by reducing pollution by 100 million tonnes per year (Sutton et al., 2021)
Adapts and builds resilience to climate change	No metrics or targets exist on adaptation and resilience building in relation to emissions reductions from fertilisers

Source: Authors

2.4 Actors and change agents in fertiliser landscape

There are various organisations who work on different aspects of fertiliser management and can potentially play a key role as change agents to help scale up measures and strategies for reducing fertiliser-related emissions. The Agriculture Innovation Mission for Climate (AIM4C), together with multiple partners from the private sector, has launched several innovation sprints (aimed at increasing non-government/private sector funding) relating to fertilisers. These included: Accelerating Synthetic Nitrogen Reductions with Nitrogen-Producing Microbes, led by Pivot Bio; Accelerating Food System Sustainability through Low-GHG Fertilizer, led by CF Industries; Climate-Resilient soil fertility management by smallholders in Africa, Asia and Latin America, led by the African Plant Nutrition Institute (APNI); the Efficient Fertilizer Consortium, led by the Foundation for Food and Agriculture Research; and Revolutionizing Nitrogen Optimization and Carbon Sequestration in Farming, led by Arable Labs and Climate-Resilient soil fertility management by smallholders in Africa, Asia and Latin America led by CIMMYT/CGIAR. Table 2.2 shows actors in the fertiliser landscape. In 2018, to the world's leading consortium on nitrogen fertiliser, the International Nitrogen Initiative (INI), committed to a global goal to halve nitrogen waste by 2030, by reducing pollution by 100 million tonnes per year, with quantified benefits for oceans, water quality, air quality, biodiversity, climate resilience and livelihoods. This pledge is being delivered through the International Nitrogen Management System (INMS), which brings together the science community, the private sector and civil society to gather and synthesise evidence to support international policy development to improve global nitrogen management (Sutton et al., 2021). Similarly, the International Code of Conduct for the Sustainable Use and Management of Fertilizers "provides a locally adaptable framework and a voluntary set of practices to serve the different stakeholders directly or indirectly involved with fertilizers" (FAO, 2019a).

Staff member of Mazingira Centre experimenting with a biodigester breaking down manure to produce biogas and nutrient-rich fertiliser.
Daniel Girma Mulat / ILRI

TABLE 2.2 **Actors and change agents in the fertiliser management landscape**

Role	Reducing emissions from fertilisers
Long-term vision and action plan	International: UNEP/GEF International Nitrogen Management System (*https://www.inms.international/*), FAO through its International Code of Conduct for the Sustainable Use and Management of Fertilizers (FAO, 2019a), CGIAR, IFDC National: Relevant ministries (Agriculture Ministry/Environment and Climate Change Ministry)
Demand creation and management	International: UNEP, UNDP, FAO, IFAD, World Bank, IFA Regional: Various regional bodies, e.g., EU, African Union, G7, G20 Donors and Foundations: BMGF, Rockefeller National: Relevant ministries and civil society
Infrastructure and supply chains	Private sector fertiliser companies: Yara International, The Mosaic Company, Nutrien and CF Industries, Syngenta Fertiliser companies with a sizeable organic fertiliser business: Nature Safe, BioStar Systems, Italpollina SpA, Krishak Bharati Cooperative Limited, Coromandel International Limited, Tata Chemicals Limited, AgroCare Canada, Inc, Sustane Natural Fertilizer, Inc, ILSA SpA, Midwestern BioAg, National Fertilizers Limited, The Scotts Miracle-Gro Company Logistics/Transport: Cargill and Maersk
Finance and investment	International: Green Climate Fund, IFC Private sector: Yara International, Syngenta Impact investors: Acumen Fund, Generation Investment Management Sustainable Solutions Fund
Research and innovation	CGIAR, and particularly its Centers like Alliance of Bioversity International and CIAT, CIMMYT, IRRI and IITA; IFDC; APNI; Wageningen University; University of Nebraska-Lincoln – The Department of Agronomy and Horticulture; Cornell University – The Department of Soil and Crop Sciences; Efficient Fertiliser Consortium by the Foundation for Food and Agriculture Research
Market structures	IFA, IFDC, UNEP, private sector (e.g., Pivot Bio; CF Industry, etc.);
Standards and certifications	IFA; IFDC; SAI and its Fertilizer Sustainability Framework; Global GAP and its GRASP standard; RSB Various regional and national agencies which set standards
Trade conditions	WTO, IFA
Knowledge, capacity and skills	CGIAR Centers, IFDC, APNI, International Potash Institute, INI and FAO
Social engagement and impact	Farmers' organisations at international and national levels, e.g., IFAP and the NFU (USA); CGIAR and relevant research universities who undertake dissemination work
Landscape coordination	FAO, IFA

Source: Authors

Notes: BMGF = Bill & Melinda Gates Foundation; CIAT = International Center for Tropical Agriculture; CIMMYT = International Maize and Wheat Improvement Center; IFAP = International Federation of Agricultural Producers; IFC = International Finance Corporation; IFDC = International Fertilizer Development Center; IITA = International Institute of Tropical Agriculture; IRRI = International Rice Research Institute; GAP = Good Agricultural Practice; GRASP = Global GAP Risk Assessment on Social Practice; NFU = National Farmers Union (USA); RSB = Roundtable on Sustainable Biomaterials; SAI = Sustainable Agriculture Initiative Platform; UNDP = United Nations Development Programme; UNEP = United Nations Environment Programme; UNEP/GEF = Global Environment Facility at United Nations Environment Programme; WTO = World Trade Organization.

2.5 Barriers to implementation

Even though some of the technologies and approaches described in the previous section are already technologically mature, largely market-ready and could potentially be scaled up (e.g., slow-release fertiliser, chemical and biological inhibitors and coated fertilisers; precision nutrient management such as sensor-based fertiliser management; and use of decision support systems for fertiliser recommendation), several barriers remain that impede upscaling. On the other hand, certain other technologies like green ammonia, blended fertilisers (when two or more fertiliser materials are mixed together) and fertigation need further RD&D before they are ready to be scaled up.

2.5.1 Technology and capacity barriers

Production of green fertilisers and enhanced efficiency fertilisers (EEF) often requires new technological knowledge that is still in its infancy even in the Global North and is not readily available in the Global South (Dimkpa et al., 2020). While various forms of precision fertilisation techniques are mature in terms of research and development, their application in the field requires a certain level of technical knowledge which farmers often lack. For example, the use of soil and plant sensors or decision support systems for SSNM requires technical knowledge to operate and then interpret and implement data (Pampolino et al., 2012). Farmers, particularly in the Global South, need training and education to effectively use these technologies and make informed decisions regarding fertiliser application.

2.5.2 Data and digital divide as a barrier

Field application of many precision nitrogen management technologies relies on accurate and up-to-date data regarding indicators such as soil nutrient levels, crop requirements and weather conditions, and the use of digital tools and connectivity to collect and analyse such data for real-time decision making (Sapkota et al., 2021). However, accessing reliable data can be challenging, especially in resource-constrained settings or regions (called "data poor regions" by Jones et al. (2017) and identified as a major limitation to enhancing agriculture-related modelling) with limited infrastructure and connectivity for data collection and monitoring (Trivedi & Dutta, 2020). In developing countries, data that can be used in analytics to inform improved fertiliser recommendations are scattered across different institutions and repositories, requiring collation and standardisation. As such, blanket fertiliser recommendations are still in use in some of these regions, resulting in poor fertiliser use efficiency.

2.5.3 Financial barriers to adoption

Green fertilisers still have higher production and distribution costs, making them more expensive compared with traditional fertilisers, which acts as a disincentive for farmers to adopt these technologies. For example, the cost of electrolysis of water makes green ammonia production 1.5 times more expensive than fossil fuel-based ammonia production (*https://www.precedenceresearch.com/green-ammonia-market*). Field application of precision fertiliser management techniques also involves the use of advanced technologies and equipment, which can be expensive to acquire and maintain. Further, many of these types of equipment and technology are highly specialized with limited use, and costs are not usually recoverable if use is discontinued (Schimmelpfennig, 2016).

2.5.4 Policy and regulatory constraints

Existing policies and regulations often act as disincentives for the adoption of precision fertiliser management practices (Oenema et al., 2011; van Grinsven et al., 2015). The absence of clear guidelines and regulations can also create uncertainty for farmers and agribusinesses. For example, the fertiliser policies of countries in the Global South (e.g., India) focus on making fertiliser available to farmers at affordable prices and increasing fertiliser consumption, while neglecting the efficiency aspects of fertiliser production (Sharma et al., 2022; Sharma & Thaker, 2011).

2.6 Recommendations for reducing emissions from fertilisers

2.6.1 Strengthen existing international collaborations to upscale scale-ready technologies, conduct RD&D for new technologies and build capacity of stakeholders

International collaborations for knowledge sharing and RD&D for scaling up technologies that are mature and scale ready is essential for reducing GHG emissions from fertilisers while increasing the co-benefits of productivity gains and healthier ecosystems. We recommend that existing international collaborations among advanced research institutes be strengthened to fill the gaps in knowledge that prevent the adoption of scalable fertiliser technologies and that such bodies invest in RD&D to further make other innovative fertiliser technologies, which are in various stages of development, scale ready. For example, further RD&D is needed for technologies which are not yet scale ready (e.g., green ammonia, blended fertilisers, fertigation). The Global Research Alliance on Agricultural Greenhouse Gases (GRA), the UNEP/GEF-coordinated INMS, and INI (Masso et al., 2020) are some of the important international collaborations. The GRA brings together over 60 countries and research institutions to find innovative solutions to mitigate agricultural GHG emissions. Through research, policy development and capacity building, the INMS aims to promote sustainable nitrogen management practices that can help mitigate GHG emissions. CGIAR and its Centers, particularly the International Maize and Wheat Improvement Center (CIMMYT) and the International Institute of Tropical Agriculture (IITA and IRRI), also conducts research in this space. New collaborations include the Efficient Fertiliser Consortium by *the Foundation for Food and Agriculture Research* (FFAR). Together, all these players should come together and, through consultative processes along with major private sector companies, help devise tangible pathways for promotion of mature and market-ready fertiliser technologies, while also conducting RD&D for making emerging technologies scale ready. In the context of innovative fertilisers, the market-ready options include slow-release fertiliser, chemical and biological inhibitors and coated fertilisers, and precision nutrient management such as sensor-based fertiliser management and use of decision support systems for fertiliser recommendations.

We also recommend that the same collation of international partners mentioned above works with national agricultural research and extension agencies (NARES) and with the private sector to build the capacity of farmers and extension agencies and private sectors, including decision support tools for farmers. Concrete examples of these capacity-building events could include promoting farmers' awareness of fertiliser technologies, supporting NARES to breed crop varieties for increased NUE, exploring innovative technologies for nutrient recycling and developing advanced sensor technologies to accurately measure soil nutrient levels for real-time fertility management.

2.6.2 Repurpose agricultural subsidies to fund scaling and RD&D on innovative fertiliser technologies

New emerging technologies (e.g., green ammonia) are more expensive than existing ones, and costs of adoption of some of the scale-ready technologies, such as precision agriculture, also remain high, creating cost barriers. We recommend that the Policy Dialogue on Transition to Sustainable Agriculture (hence forward referred to as PD throughout the report), launched concurrently and co-led by the World Bank Group and UK, should prioritise the formulation of indicative guidelines regarding repurposing subsidies to transition to low-emission/cleaner fertilisers. Action could include international collaborative research/policy dialogue and the commissioning of a white paper on repurposing subsidies for transitioning to cleaner fertilisers, under various policy and socioeconomic contexts. It should also recommend ways of overcoming cost barriers through regulatory reforms.

2.6.3 Develop international collaborations for harmonisation and regulation of market standards for new and innovative fertilisers

We recommend harmonisation of regulation and market standards for the newer low-emission fertilisers (e.g., slow-release fertilisers, coated fertilisers and green fertilisers) to facilitate standard and equitable trade in these products, particularly in the countries that are significant producers, consumers and traders of fertilisers, such as the USA, China, Brazil, India and the EU member states. The GRA, the UNEP/GEF-coordinated INMS and the INI are some of the important actors that can help in the process, while the PD can provide a forum for government policymakers to create dialogues and share their domestic experiences. Such domestic experiences include relevant clauses of the Common Agricultural Policy (CAP) of the EU (Pe'er et al., 2019) and China's "Zero-Growth" fertiliser policy that incentivises adoption of low-emission fertilisers (Ji et al., 2020; Jin & Fang, 2018). Incentives for the use of low-emission fertilisers have also been adopted in developing countries, such as Brazil's Low Carbon Agriculture Programme (Angelo, 2012) and India's Soil Health Card Scheme (Reddy, 2019). Providing incentives to the private sector can be justified if the behavioural changes lead to the generation of public goods such as environmental services. Any such development of standards and norms for harmonisation needs to consider the International Code of Conduct for the Sustainable Use and Management of Fertilizers (*https://www.fao.org/3/ca5253en/ca5253en.pdf*). This is an important tool for implementing the Voluntary Guidelines for Sustainable Soil Management, with special regard to nutrient imbalances and soil pollution.

2.6.4 Further strengthen international partnerships to improve data and digital connectivity

Data and digital infrastructure play a critical role in reducing emissions from fertilisers. We recommend that international partnerships are further strengthened to improve data and digital connectivity. The INMS, the Technical Centre for Agricultural and Rural Cooperation (CTA), which supports information and communications technology (ICT) use in agriculture through programmes like the Digitalization of African Agriculture (D4Ag), and the Global Open Data for Agriculture and Nutrition (GODAN) initiative, which promotes open data in agriculture to address the world's food security and environmental challenges, are examples of international efforts that address these needs. Availability of sufficient data, approaches to data management and suitable modelling methods have been identified as limitations in enhancing the decision making of multiple stakeholders in less developed countries (Jones et al., 2017).

2.6.5 Improve fertiliser recommendations in developing countries through actions by NARES and private sector

Farmers' production environments are quite heterogeneous, and often farmers are not given the right information about fertilisation application, particularly in developing countries. Moving from blanket fertiliser recommendations to more site-specific recommendations will improve fertiliser use efficiency and resulting profitability, as well as reducing GHG emissions. Supporting LMICs to develop agronomy databases, access climate data and integrate these through analytics, including application of crop modelling, is necessary to refine the existing blanket fertiliser recommendations. NARES and the private sector can collaborate to devise such science-based and region-specific norms. Table 2.3 sums up the recommendations.

TABLE 2.3 **Recommendations for promoting technologies to reduce emissions from fertilisers**

Summary of recommendations	Relevant partners for implementation	Recommendation applicable at levels		Themes*
		Domestic	International	
Strengthen existing international collaborations among advanced research institutes to fill gaps in knowledge that prevent adoption of scalable fertiliser technologies. Invest in RD&D to further make other innovative fertiliser technologies, which are in various stages of development, scale-ready for market uptake and for capacity building of NARES and extension agencies	GRA, INMS, INI and the CGIAR	✓	✓	Themes 4 and 5
Formulate concrete pathways and associated guidelines for repurposing agricultural subsidies to transition to low-emission/ cleaner fertilisers	PD		✓	Theme 2
Harmonise regulation and market standards for the newer low-emission fertilisers (e.g., slow-release fertilisers, coated fertilisers and green fertilisers) to facilitate standard and equitable trade	GRA, INMS, INI, PD		✓	Themes 3 and 5
Strengthen international partnerships to improve data and digital connectivity to share information on innovative fertilisers	INMS and CTA	✓	✓	Themes 2 and 3
Provide site-specific information to improve fertiliser use efficiency, particularly in developing countries	NARES and private companies	✓		Themes 2 and 4

Source: Authors
Notes: * Theme 1: Climate finance; Theme 2: Policies, regulations and innovations; Theme 3: Metrics, indicators and standards; Theme 4: Research and development and demonstration (RD&D); Theme 5: Private sector, markets and trade

2.7 Gaps in scientific knowledge

Various tools, techniques and strategies have been developed to improve NUE in the field, increase yield and reduce environmental footprint. However, many of these technologies have not been adopted widely by producers. Research should focus on adapting these technologies under diversified production environments, identifying drivers and barriers of adoption, and developing technologies for efficient extraction of fertilisers from organic sources. Breeding crop varieties for increased nutrient use efficiency and nitrification inhibition can help enhance nutrient uptake efficiency and reduce nutrient losses to the environment. There is a need to develop efficient, cost-effective and safe methods to recycle and recover nutrients from agricultural residues, food waste and sewage sludge. Research should focus on exploring innovative technologies such as residue recycling and legume integration in cropping systems, and refining technologies around anaerobic digestion, composting and vermicomposting.

Advanced sensor technologies should be developed to accurately measure soil nutrient levels, crop nutrient demands and real-time nutrient status. Remote sensing and GIS should be integrated into soil fertility management to address the spatial and temporal variability of nutrient status and plant nutrient requirements. There is a need to develop adaptive nutrient management strategies that account for changing climate conditions, and to mitigate associated risks. Nutrient management tools, techniques and strategies should be evaluated using a multi-criteria indicator for agronomic performance, economic profitability and environmental safeguards.

2.8 Conclusion

Fertiliser use is a leading cause of GHG emissions in the agriculture sector, but patterns of fertiliser use are highly uneven. For example, China, India, the USA and the EU28 account for 62% of the total fertiliser emissions to date (Menegat et al., 2022), but there are less developed countries with highly significant deficits in fertiliser use (Snapp et al., 2023). Reducing the overall production and use of synthetic nitrogen fertilisers offers significant mitigation potential and, in many cases, realisable absolute emission reduction potential in regions with intensive fertiliser use. However, in other regions with fertiliser deficiencies, alternative methods need to be explored to balance food production with fertiliser use and GHG. In this section, we have discussed various technologies and strategies that are available and potentially scalable for reducing GHG emissions from fertilisers. While many of these strategies are being adopted, the pace and scale of adoption is not enough to keep to the Paris Agreement goals. Agroecological and other sustainable approaches which focus on long-term soil fertility improvements through natural processes are important in this context and are discussed in detail in Section 7. These technologies often have positive co-benefits for the environment, including improvements in land and water quality. However, emissions reduction and environmental co-benefits from fertilisers are but two of the four objectives of the Agriculture Breakthrough Agenda. Table 2.4 provides a qualitative, expert judgement of the potential of the various technologies discussed in this section against the four criteria of the Agriculture Breakthrough.

TABLE 2.4

Qualitative assessment of fertiliser emission reduction technologies and strategies across the four breakthrough principles

Strategies for reducing emissions from fertilisers	Sustainably increases agricultural productivity and incomes	Reduces GHG emissions	Safeguards soil, water resources and natural ecosystems	Adapts and builds resilience to climate change
Measures to reduce emissions from fertiliser production processes	Low	Medium–high	Low	Low
Precision fertiliser management technologies	High	Medium–high	High	High
Low-emission fertilisers	Low–medium	Low–medium	Low–medium	Low
Nitrification inhibitors	Low	Medium	Medium	Low
Biological nitrogen fixation	Medium	Medium	High	Medium
Organic fertilisers and biochar	Low	Low	Low–medium	Medium

Source: Author's expert judgement based on available evidence presented in Section 2.2. Note that this is not a rigorous evidence synthesis or systematic review-based analysis and, as such, needs to be interpreted with care.

National governments, particularly in the Global North, have a key role in promoting widespread adoption of these technologies by providing standards, financial incentives, development funding and research, as well as regulatory support. Countries in the Global South will need additional financial resources and technology support and international collaborations in the form of finance, research and development support and technology transfer, as well as policy reforms, which will be important drivers for technology adoption in this area. Additional areas of international collaboration will include the sharing of information and best practices, standardisation and policy coordination.

Worms are one of the proteins and part of the diet in Zamia, part of the Miombo Products in Zambia.
Laura German / CIFOR

3 Alternative proteins

Core authors: **Claudia Ringler, Douglas Merrey, Shakuntala Thilsted**

KEY HIGHLIGHTS

- Alternative proteins have a strong potential to reduce the environmental footprint of traditional animal-source foods (ASF). They generally have lower greenhouse gas emissions and use less soil and water resources and natural ecosystems.
- Strengthening their role vis-à-vis traditional ASF will likely support resilience to climate change.
- Their impacts on agricultural incomes and productivity need more study.
- Key challenges to the large-scale adoption of some types of alternative proteins include: (1) weak regulatory frameworks; (2) economic constraints, including their high cost; and (3) consumer acceptance.

3.1 The context

Animal-source foods (ASF), such as meat, milk, eggs and fish, are an important component of diverse diets and particularly beneficial to children, helping them to reach their optimal growth and development potential (Asare et al., 2022). Over the past 50 years, global meat production has increased threefold, reaching 340 million metric tonnes in 2018, and milk production has doubled, reaching 918 million metric tonnes in 2021. Per capita meat production nearly doubled from 23 kg in 1961 to 43 kg in 2020, indicating that growth in meat production has outpaced population growth. HICs in Europe, North America and Australia consume between 80 kg and 120 kg per year (as measured in meat supply quantity per capita), while some African countries consume less than 10 kg per capita per year. Consumption of ASF, including meat, is correlated with incomes, with the highest growth rates in consumption happening in countries such as China, Brazil and South Africa, which have undergone rapid economic growth in the last several decades. On the other hand, India, for cultural and religious reasons, is an exception to this trend (Ritchie et al., 2017). The demand for traditional ASF has largely plateaued in most HICs, although it remains much higher than global averages.

At the same time, global demand for ASF is projected to rise substantially by 2050, particularly in LMICs as their incomes increase; currently, their consumption of high-quality proteins remains low, largely due to the high cost. In 2020, an estimated 3.1 billion people could not afford a healthy diet, including ASF, vegetables and fruits (Colgrave et al., 2021; FAO et al., 2022).

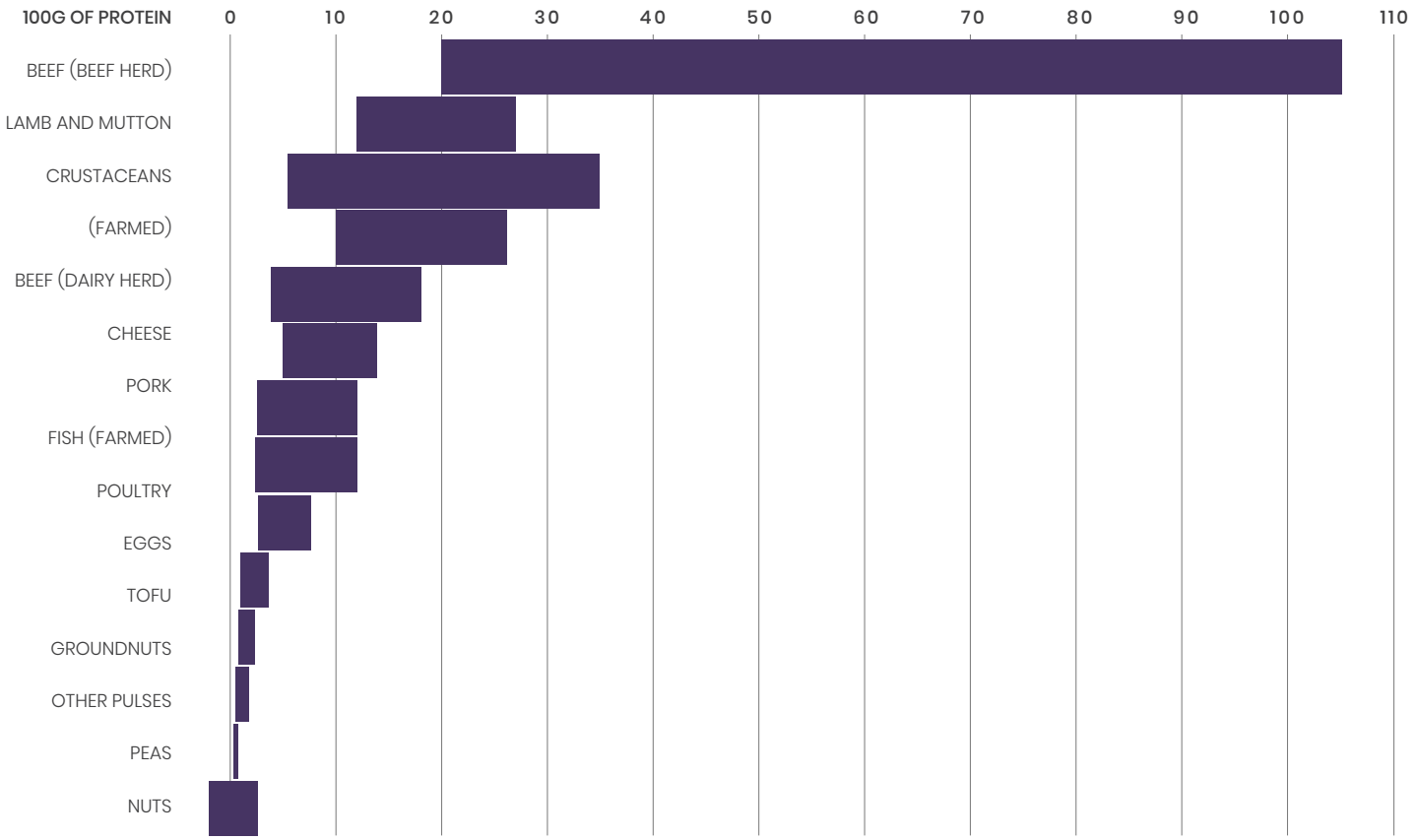
High-quality protein foods, such as most types of ASF, have a high GHG footprint, with livestock and fisheries estimated to account for 53% of food emissions, including production, land use and animal feed, but excluding their share in supply chain emissions (supply chain emissions are estimated at 15% of total food emissions) (Poore & Nemecek, 2018). Emissions per quantity of protein produced are particularly high for beef and often higher in LMICs due to inefficient production technologies (Figure 3.1 presents a range of emissions for high- and low-impact producers; Poore & Nemecek, 2018). Livestock production, moreover, has a particularly high land and water footprint (Vanham et al., 2023; Heinke et al., 2020; Ritchie et al., 2017; see also Section 6.1) and is considered a leading cause of deforestation, particularly in the tropics (Pendrill et al., 2022).

'Alternative proteins' is a broad term that refers to any protein-rich foods and food products intended to replace those derived from traditional livestock sources such as meat, eggs, dairy products and fish. They include food products made from plants (e.g., grains, legumes and nuts), micro-organisms (e.g., fungi or mycoproteins, algae and seaweed), insects (e.g., crickets, mealworms and black soldier flies) and cultivated (lab-grown) proteins (IEA, 2022), and they are used as human food and some also as animal feed. The quality of these proteins differs by protein source (Herreman et al., 2020). Apart from cultivated meats and mycoproteins, all other forms of alternative proteins, such as legumes, nuts and insects, have been a part of traditional diets in many parts of the world and as such are not new (Costa-Neto & Dunkel, 2016). However, more traditional protein-rich foods might be cultivated, processed, packaged or marketed in different ways. Alternative proteins have the potential to reduce GHG emissions in HMICs by reducing intake of traditional ASF; in LMICs, alternative proteins could also increase access to protein, including to high-quality protein in contexts with high malnutrition, thereby reducing child stunting (Haile and Headey, 2023). Access to high-quality protein in LMICs can be achieved either directly, through the availability of affordable alternative proteins, or indirectly, through lower prices and increased accessibility of traditional ASF due to a reduction in consumption in HMICs. Importantly, there is no universally agreed upon definition of alternative proteins; the definition maintained here is broad and follows the 2022 Breakthrough Agenda Report.

FIGURE 3.1

Greenhouse gas emissions of selected traditional protein foods

GHG emissions in kg CO^2e per 100g of protein



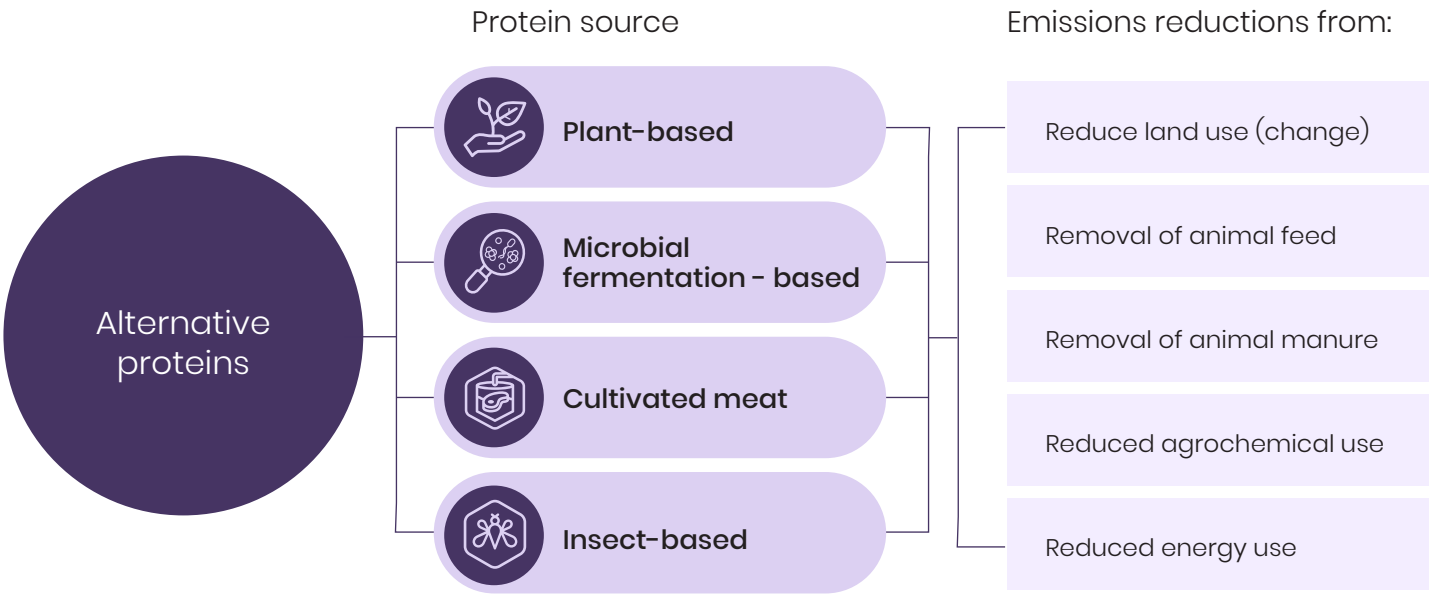
Source: Poore & Nemecek, 2018

Alternative proteins aim to provide a similar – and sometimes the same – high-quality nutritional value to ASF but with a lower environmental (land, water, chemicals, energy) footprint, including for GHG emissions, and without animal slaughter, hormones, antibiotics or food-borne pathogens; with an extended shelf life; with the same taste, texture and chemical structure; and at a lower cost. However, data and analyses on newer forms of alternative proteins remain limited due to the recent emergence of such proteins and proprietary production processes. A wide range of products under the alternative protein heading – produced by both established private food firms and start-ups – are already in markets, mostly in HICs and mostly from plant-based proteins, but there is incipient growth in LMICs as well. Market shares for alternative protein foods remain small for most products, with a few exceptions for some products and geographies; these include the plant-based milk market, which accounts for 15% of the milk market in the USA (GFI, 2023). The alternative protein market has been growing rapidly, albeit from a low base, and in 2021 its value was estimated at USD 60.45 billion (Mottet et al., 2020; GMI, 2022).

3.2 Types of alternative protein

This section covers: (1) plant-based alternatives to meat products; (2) microbial fermentation-based proteins; (3) cultivated meats derived from animal stem cells; and (4) insect-based proteins. It examines their potential impact on GHG emissions, natural resources (soil, land and water), agricultural productivity, incomes, food security and nutrition, and climate resilience. Figure 3.2 presents potential emissions reductions to which the various alternative protein sources contribute to various degrees.

FIGURE 3.2 **Opportunities for emissions reductions from alternative proteins**



Source: Authors

3.2.1 Plant-based proteins

Plant-based protein is mostly derived from protein-rich seeds and grains, such as soy and wheat, but also pea, chickpea, rapeseed and lupin, generally through dry or wet fractionation, a process used to isolate the protein fraction from the seed. Traditional wet fractionation requires the use of organic solvents and considerable water resources as well as energy-intensive drying. Dry fractionation uses less energy and no water but does not yet produce high-purity isolates (Assatory et al., 2019). Importantly, not all plant-based protein undergoes fractioning: for example, plant-based diets can integrate nuts or beans – in a 'bean burger', for instance – without processing. The focus of the breakthrough alternative protein technology, however, is on products that are deliberately created and marketed to replace traditional ASF protein. Macroalgae (seaweeds) are a further source of alternative protein, containing up to 47% protein on a dry weight basis, which is close to levels found in meat, eggs, soya beans and milk (de Souza Celente et al., 2023). Many edible mushrooms can also serve as a source of alternative protein due to their high protein content; near complete amino acid profile; and other benefits, including antioxidant, antitumour, angiotensin-converting enzyme (ACE) inhibitory and antimicrobial properties (Ayimbila & Keawsompong, 2023).

Based on a Good Food Institute (GFI) study that used a lifecycle analysis, Thornton et al. (2023) noted that, broadly, plant-based meat substitutes require 47–99% less land and 72–99% less water, emit 30–90% fewer GHG emissions and cause 51–91% less aquatic nutrient pollution compared with

factory-farmed animal meat and fish. In addition, the health benefits of adding alternative proteins to diets have been documented in populations with high meat consumption levels: for example, the partial replacement of meats with plant-based proteins can improve several cardiovascular disease risk factors (Song et al., 2016). Based on a review of the literature on plant-based animal product alternatives, Bryant (2022) notes that, while they generally have lower levels of fat, saturated fat, cholesterol and calories, and they tend to have more fibre and a range of micronutrients, they may have less bioavailable protein, iron and vitamin B12 and some products contain high levels of salt when compared with traditional ASF products. Therefore, alternative proteins are currently not directly interchangeable with ASF (van Vliet et al., 2021; Crimarco et al., 2020; Toribio-Mateas et al., 2021). To ensure their healthiness, manufactured plant-based alternatives need similar measures and approaches to those used for other foods, such as labelling, other regulations and voluntary measures.

3.2.2 Microbial fermentation-based proteins

Fermentation has been used for thousands of years in the conservation of food, such as for soy sauce, cheese, tofu, tempeh and many other products. Bacteria, algae and fungi (mycelium and yeasts) are used in fermentation processes to derive microbial-based proteins, either directly on foods to improve nutrition, taste or texture or as a platform to produce ingredients for the food industry, and to produce microbial biomass as feed or food. Both wild strains and engineered micro-organisms are used in the industry. The fermentation process can result in high amounts of protein, fibre and micronutrients and can improve the bioavailability of nutrients, although their nutritional benefits need further investigation. Live microbial supplements have been shown to improve animal feed uptake, weight and traditional milk production and to reduce the need for drugs and antibiotics (Graham & Ledesma-Amaro, 2023; Garofalo et al., 2022). Finally, new processes are being developed to convert food, lignocellulosic and food and drink industry waste into proteins (Piercey et al., 2023).

Efforts are being made to further reduce the environmental footprint of the fermentation process by improving growth and increasing the efficiency of substrate use (Graham & Ledesma-Amaro, 2023). Like the cultivation of meats, fermentation processes can be highly energy intensive. This can be addressed, to some extent, by using renewable energy sources in the production process. Moreover, the substrate used for some processes, such as glucose extracted from sugarcane, can require land, water and energy resources for its production. Using a lifecycle assessment methodology, Humpenöder et al. (2022) found that substituting 20% of per capita ruminant meat consumption with fermentation-derived microbial protein can offset future increases in global pasture area, cutting annual deforestation and related CO^2 emissions roughly in half, while also lowering methane emissions. The authors did not consider impacts on livestock producers, however.

3.2.3 Cultivated meat proteins

Cultivated meat is produced from animal stem cells that are grown in a controlled environment in nutrient-rich media. Cells are harvested in a centrifugation process and then processed into end products, sometimes with other additives. Cultivated meat and fish products are at an early stage of development. Their key environmental benefits are a reduction in land and water use, in animal feed and manure, and in agrochemical use compared with conventional ASF. Some studies suggest that the environmental impact of cultivated meat is highly uncertain due to high energy requirements, which are currently largely fossil fuel based (e.g., Alexander et al., 2017; Godfray, 2019; Rubio et al., 2020; Sinke et al., 2023). However, the rapid shift to renewable energy sources plus innovations in production processes can help address this concern in the future. Compared to plant-based protein, the nutritional profile of cultivated meats is closer to traditional meat, and its fat profile can be controlled

(Thornton et al., 2023). Based on what is known about the production process, Fraeye et al. (2020) conclude that cultivated meats lack many of the minerals and vitamins considered essential for good health, although these may be obtained from other sources. Given the current high cost of producing cultivated meat, as well as several other challenges, the market size of this alternative protein subsector is still very small.

3.2.4 Insect-based proteins

Entomophagy – the practice of eating insects – is common in many places. Over 2,000 insect species are consumed by humans in 119 countries (Alexander et al., 2017). Farmed insects are an alternative protein source that can reduce multiple environmental impacts while providing a high-quality source of protein for both food products and livestock (including fish) feed (Alexander et al., 2017; Verner et al., 2021; Smetana et al., 2016; Jensen et al., 2021; Hazarika & Kalita, 2023; van Huis & Gasco, 2023). Insects are highly efficient in terms of water and space requirements compared with many other protein sources and are rich in fat, vitamins, minerals and calories (Hazarika & Kalita, 2023). Insect farming uses low-value organic waste to quickly produce nutritious and protein-rich foods for humans, fish and livestock and biofertilisers for soils (van Huis & Gasco, 2023; Verner et al., 2021). Hazarika & Kalita (2023) found that, while insect-based protein is growing rapidly in use and offers many nutritional and environmental advantages, it also poses potential health risks, such as allergens, that need further study and careful regulation. Other concerns include animal welfare, consumer acceptance and, in some environments, energy needs for production.

CASE STUDY 3.1

Rearing black soldier flies in Kenya

In 2019, the International Centre of Insect Physiology and Ecology (ICIPE) trained youth in insect production. Thus began Y Minds Connect, a group of 100 youth who started a business raising black soldier flies (BSF) on organic waste. They now produce 1,500 crates of BSF larvae per month and sell dried insects, BSF-based pet food and insect manure under the brand name Vihanga. However, they face challenges, such as the high cost of outsourcing drying services, and are exploring partnerships with private actors, financial institutions and the county government for funding options. In the meanwhile, ICIPE has also trained over 5,000 Kenyan farmers on how to raise and use BSF feed as a supplement.

Sources: International Development Research Centre (*https://www.idrc.ca/en/stories/insect-rearing-takes-amongst-kenyan-youth*); Rockefeller Foundation (*https://www.rockefellerfoundation.org/case-study/black-soldier-flies-inexpensive-and-sustainable-source-for-animal-feed/*).

CASE STUDY 3.2

Use of microbial-based cultured milk protein for humanitarian settings

Dairy and Formo using precision fermentation and synthetic biology, with bacteria and yeast as the organism, for subsequent use as ingredients in the food industry. For example, Perfect Day's milk protein is now on the US market in the form of milk, ice cream, cream cheese and cake mix and as whey protein powder. As costs of microbial-based proteins come down and regulatory frameworks are developed, whey protein powder can be used in food supplements in humanitarian settings and for improving the diets of food-insecure children in LMICs.

Sources: Graham & Ledesma-Amaro, 2023; *https://www.defeatdd.org/blog/cultured-proteins-healthy-children-and-healthy-planet*.

3.3 Metrics for measuring progress

Developing a full set of relevant metrics for alternative proteins is complex because of the large number of dimensions that must be measured and the high degree of uncertainty about the potential impacts. These dimensions and challenges include, but are not limited to: comparative nutritional value (comparing different types of alternative proteins with each other and with proteins in traditional ASF, and comparing alternative protein foods with traditional ASF); overall impacts of a switch to alternative proteins using lifecycle analyses in terms of their techno-economic, environmental and social dimensions as well as the overall structure of the industry; and impacts of a substantial shift to alternative proteins both on large-scale commercial meat, dairy and fish producers and on smallholder producers. We recommend giving priority to developing practical, science-based metrics to measure the longer-term outcomes of transitioning to a higher share of alternative proteins in both human and animal diets, through collaborative action. Such collaborative action on metrics for measuring progress would benefit from more data and more transparency around existing data. However, there is a strong consensus in the literature that alternative proteins are generally more environmentally friendly than meat products (e.g., Smetana et al., 2015; Smetana et al., 2016; Detzel et al., 2022; GFI, 2022; Bryant, 2022; Humpenöder et al., 2022).

3.4 Actors and change agents in the alternative protein landscape

Man buying vegan milk in the North East of England
iStock

For advocacy at the global level in favour of switching from animal sources to alternative proteins, GFI, the United Nations Framework Convention on Climate Change (UNFCCC) and the *EAT-Lancet Commission* are important change agents. Within countries, the private sector (especially new start-ups), non-governmental organisations (NGOs) and scientists can play a critical role, as do governments. The AIM4C, together with multiple partners from the private sector, has launched several innovation sprints relating to alternative proteins, including those on innovative fermentation technologies, sustainable protein innovation and cellular agriculture. Given the relative novelty of many alternative protein foods, the actor landscape is developing and changing rapidly. Table 3.1 lists potential change agents and their roles. Their respective roles are further described in Section 3.6.

TABLE 3.1 **Actors and change agents in the alternative proteins landscape**

Role	Alternative protein actors
Long-term vision and action plan	GFI; EAT-Lancet Commission; universities; FAO; CGIAR; UNFCCC; WRI, EIT Food co-funded by the EU
Demand creation and management	National governments; private firms (producers and marketers); associations (e.g., API and Fungi Protein Association); medical and nutrition professionals
Infrastructure and supply chains	Private firms including those involved in the AIM4C sprints (e.g., Nature's Fynd and Aleph Farms) and investors (e.g., VisVires New Protein)
Finance and investment	National governments (research and regulation); private investment firms and venture capitalists (e.g., CPT Capital, Strauss Group, Synthesis Capital and Sustainable Food Ventures); World Bank and regional development banks in LMICs; foundations and alliances (e.g., Rockefeller Foundation, Climate Works Foundation and Climate and Land Use Alliance); investor coalitions (e.g., FAIRR Initiative, Asia Research and Engagement)
Research and innovation	Universities; CGIAR; Global Climate Forum; WRI and other think tanks (e.g., Food Tank); climate advisors taking part in relevant AIM4C sprints; GFI
Market structures	National and regional governments
Standards and certification	National governments, with input from universities and other partners (e.g., *Alternative Proteins Framework*)
Trade conditions	WTO; national governments
Knowledge, capacity and skills	National governments; consumer organisations; universities
Social engagement and impact	Consumer organisations
Landscape coordination	FAO; UN Climate Change High-Level Champions; Committee on World Food Security; Codex Alimentarius Commission; Food and Land Use Coalition; GFI

Source: Authors
Notes: API = Alternative Protein International; WRI = World Resources Institute; WTO = World Trade Organization.

3.5 Barriers to implementation

In addition to the overall limited knowledge of the impacts of alternative proteins, the major barriers to production and consumption of alternative proteins at scale include: (1) weak regulatory frameworks; (2) economic constraints and high costs; and (3) consumer acceptance.

3.5.1 Weak regulatory frameworks

Novel alternative proteins need to pass a series of regulatory approvals that are generally not sufficiently readied for such foods, particularly those where engineered species and new production processes are used. Currently, food safety reviews and authorisations need to be obtained separately for each country. Processes can be accelerated when approved production processes are used, when alternative proteins are used as animal feeds, and when foreign DNA and living cells are removed. GFI (2022) lists Canada, European countries such as Denmark, Israel, Qatar, Singapore and the USA as countries with substantial interest and investment in plant-based and cultivated proteins.

Kreis et al. (2019) assessed the policy and regulatory environment and potential scaling pathways for precision fermented milk and egg proteins in the EU, the USA and two selected LMICs – Ethiopia and India. They found that the USA had the most clearly defined regulatory pathway for milk and egg protein products, whereas it was not clear how the EU would define them. In Ethiopia and India, food safety regulatory institutions were at an early stage of development, but they were likely to follow the pathways of HICs. The use of genetically modified cells in the manufacturing process and labelling issues increase regulatory costs (Morach et al., 2022).

3.5.2 Economic constraints and high costs

The private sector dominates alternative protein investment, while the public sector has yet to significantly engage. According to a GFI assessment, the sector attracted USD 14.2 billion in private capital over a decade, "with annual investments nearly doubling every year on average" (O'Donnell & Murray, 2023: 83). Much of the industry has high entry costs, preventing smaller firms from engaging. Together with weak regulatory regimes, this has affected the costs of some fermentation-based foods as well as cultivated meats and fish and has made it difficult for companies to reach a sustainable scale. Instead, it favours market concentration. In addition to start-ups, approximately half of the world's largest global meat, dairy and seafood companies are investing in the alternative protein market (O'Donnell & Murray, 2023). Barriers to entry are lower for insect-based proteins, seaweed and the edible mushroom markets compared with microbial fermentation, cultivated meats and some plant-based alternatives.

Subsidies for the dairy sector and the traditional agriculture sector in general have also stymied investments in alternative proteins and novel foods. Such support is encouraging the externalisation of the costs of agriculture in terms of health and environmental impacts. According to Oenema et al. (2011) and Vallone & Lambin (2023), public support during 2014–2020 in the EU and the USA was more than 800 and 1,100 times greater, respectively, for traditional livestock production than for alternative protein options. The limited support that was available for research and innovation was provided for early-stage innovation, process optimisation and scaling. The authors suggest that tying public investment to stronger environmental requirements, considering environmental implications in food-based dietary guidelines (FBDGs) and reducing restrictions on the naming of alternative protein foods (such as calling soya milk 'milk') are some of the measures that could reduce the economic constraints on the alternative protein sector. The focus of subsidies on traditional ASF and the lack of public investment in research and development discourage investment in alternative protein foods and contribute to their higher prices. Public policies, including subsidies focused on traditional livestock production in HICs, should be redirected to increase the efficiency of the entire food system to deliver healthy diets, a healthy planet and reasonable profits (Benton & Bailey, 2019). Finally, the lack of public sector engagement in alternative proteins has contributed to the paucity of open-access research and development, which limits assessment of opportunities and challenges.

3.5.3 Consumer acceptance

Consumer acceptance differs by type of alternative protein food and geography. Some studies find that consumers perceive some alternative proteins, such as plant-based and fermentation-based vegetarian options, to be healthier and less harmful environmentally than traditional ASF. Other consumers are concerned that some alternative proteins are "unnatural", overly processed and even unhealthy because of concerns over additives (Bryant, 2022). Onwezen et al. (2021) systematically reviewed 91 articles on the drivers of consumer acceptance of five alternative proteins in Western countries: pulses, algae, insects, plant-based alternative proteins and cultured (cultivated) meat. They

found that the acceptance of alternative proteins was relatively low compared with meat. Vallone & Lambin (2023) note limited to no reflection of alternative protein options in national dietary guidelines and public procurement policies in the USA and EU, as well as initiatives to ban or limit the use of traditional ASF names for alternative protein foods. Changes in these areas can improve consumer acceptance.

3.6 Recommendations for promoting alternative proteins

International collaborations are needed to overcome the key challenges of the lack of knowledge and data on alternative proteins, weak regulatory frameworks, economic constraints and poor consumer acceptance. Such collaborations are described in the following sections.

3.6.1 Collaborations on RD&D for filling knowledge gaps on the impacts of alternative proteins

There is consensus that alternative proteins generally have a lower environmental footprint than proteins from traditional ASF. However, knowledge gaps remain on specific environmental impacts (on land, water, energy and emissions), on many of the social and economic impacts (for example, whether alternative proteins will increase or reduce employment overall in the global protein sector), and on the health and nutrition impacts of different alternative proteins. RD&D-related collaborations are needed to seek data from public and private sector investors, and to assess these impacts in various contexts (e.g., HICs versus LMICs). CGIAR, FAO, the GFI and the World Resources Institute (WRI) should set up working groups and collaborative consultative mechanisms by bringing in experts from multiple disciplinary backgrounds to fill these research gaps. Such collaborations should involve policymakers, private sector actors and national research institutes, including from LMICs. To support the latter, governments in HICs should co-invest in open-source research with the private sector and should develop joint research on this topic with LMICs.

3.6.2 Collaborations for setting common standards and labelling

To enable alternative proteins to fulfil their breakthrough role for climate resilience, we recommend increased international collaboration for developing common definitions, standards, metrics and labelling norms, as well as common methodologies for assessments of environmental, social, health and nutrition impacts and for ensuring overall food safety of alternative proteins (Kreis et al., 2019). FAO, the Codex Alimentarius Commission (e.g., FAO and WHO, 2021), the International Organization for Standardization (ISO), GFI, WRI and CGIAR could collaborate in these tasks by setting up working groups and collaborative consultative mechanisms. Knowledge exchange needs to commence as soon as possible and cannot await an internationally agreed Codex Alimentarius standard. Respect for food habits and cultures needs to be considered and LMIC groups and countries included. Private sector companies, particularly those participating in the current AIM4C sprints related to alternative proteins and investor coalitions, should also participate in such endeavours.

3.6.3 Collaborations for developing science-based compatible regulatory frameworks and policies

Currently, the development of legislative and regulatory frameworks for alternative proteins are focused on HICs, with LMICs just starting to address the issue. While regulatory frameworks and policies are a national prerogative, international collaboration is urgently needed; this would include sharing experiences and adapting existing frameworks, such as the Alternative Proteins Framework, to different settings. Without transparent processes and the engagement of consumers and other food-system

stakeholders, processes may favour large commercial interests, discourage innovation, or be based on inadequate scientific evidence. This is an area where capacity building for countries with limited engagement to date is important and where a permanent knowledge exchange platform should be developed.

3.6.4 Increased public investments for RD&D and policy support

Public investments in RD&D and policy support are needed to make alternative proteins a reliable and affordable option everywhere – in HMICs, to replace high levels of ASF intake; and in LMIC contexts with high levels of malnutrition, to reduce child malnutrition through the use of high-quality protein sources.

The alternative protein sector is dominated by private sector investments. While these are suitable in most HIC contexts (although data access (see Section 3.6.1) and regulatory concerns (Section 3.6.3) remain), public investments in both RD&D and policy formulation will be needed to help scale alternative proteins beyond initial private sector investment in a few HICs, particularly for high-risk discovery. An analysis commissioned by the UK Foreign, Commonwealth and Development Office (FCDO) and the ClimateWorks Foundation estimates that governments worldwide need to commit USD 4.4 billion per year to research on alternative proteins (ClimateWorks Foundation & FCDO, 2021). Public policy support is also needed in the following areas: the inclusion of alternative foods in public food procurement rules; their consideration in FBDGs; and the inclusion of environmental risks and concerns, including climate risks, in public investments in all protein-rich foods, as well as in national and international climate commitments, such as the Nationally Determined Contributions (NDCs). Governments in HICs, large private foundations and private sector companies, including the retail sector, should fund research and policy consultations in partnership with researchers and the private sector from LMICs. The PD should launch international collaborative research and policy dialogues to suggest concrete ways of repurposing agricultural subsidies for financing such RD&D collaborations.

3.6.5 Collaborations for raising consumer awareness

Researchers, civil society organisations and consumer groups should also be involved through the UN Climate Change High-Level Champions and other relevant platforms in raising public awareness and increasing communication on the opportunities and risks of alternative proteins. Communication would need to be adapted to the specific challenges in HIC and LMIC contexts, where the current intake of traditional ASF is often substantially above or below recommended levels respectively. Consumer awareness can also be shaped by government inclusion of alternative proteins in guidelines, such as those on food procurement and diets, and through wide consultations on the naming of alternative protein foods. Such collaboration needs to include all other key food-system actors that are engaged in alternative protein development and deployment, including scientists. Table 3.2 provides a summary of these recommendations and notes that some are applicable in both international and domestic contexts.

TABLE 3.2 **Recommendations for promoting alternative proteins**

Summary of Recommendations	Relevant partners for implementation	Recommendation applicable at levels		Themes*
		Domestic	International	
Collaborate on RD&D to fill knowledge gaps on environmental, social and economic impacts, as well as on the health and nutrition impacts of different alternative proteins	CGIAR, FAO, GFI, WRI, governments, national research institutes, including from LMICs	✓	✓	3 and 4
Promote international collaboration for developing common standards, metrics, labelling norms and common methodologies for the assessment of environmental, social, health and nutrition impacts and for ensuring overall food safety of alternative proteins	FAO, Codex Alimentarius Commission, ISO, GFI, WRI, CGIAR		✓	3 and 5
Foster collaborations for developing compatible regulatory frameworks and science-based policies and guidelines to support the scaling of novel alternative proteins	FAO, Codex Alimentarius Commission, GFI, FAIRR Initiative, CGIAR, WRI, government agencies	✓	✓	2 and 5
Increase public investment in RD&D and policy support, with a focus on making alternative proteins a reliable and affordable option everywhere	Governments, private foundations, private companies, PD, international development banks		✓	1 and 2
Raise public awareness of the potential of alternative proteins, including their differentiated adoption potentials in HIC and LMIC contexts	Governments, other key food-system actors, including scientists	✓	✓	2, 4 and 5

Source: Authors

Notes: * Theme 1: Climate finance; Theme 2: Policies, regulations and innovations; Theme 3: Metrics, indicators and standards; Theme 4: Research and development and demonstration (RD&D); Theme 5: Private sector, markets and trade

3.7 Gaps in scientific knowledge

The science is clear on the need to drastically reduce GHG emissions from agriculture (including from livestock production) and to stop further land degradation from agricultural expansion and the degradation of cultivated soils. The science is also clear that dietary change can play a key role in addressing climate change challenges. However, the science is less clear on the pathway to enable alternative proteins to be game-changing solutions. Three major gaps emerge from the literature: (1) impacts; (2) nutritional value; and (3) costs and taste to meet consumer expectations.

There are several gaps in the science on the potential impacts of a major shift from animal products to alternative proteins. For example, the extent to which consuming different types of alternative proteins will contribute to reducing GHG emissions and to reversing the expansion of grazing and cultivated lands needs comprehensive lifecycle assessments (Allotey et al., 2023), but these do not yet exist

for all options and new processes and technologies are continually being developed. What further complicates the issue is that emission factors for intensively raised and grass-fed animals and for different livestock systems differ widely (Alexander et al., 2017), and there is a lack of transparency in the data on the production processes of alternative proteins.

The potential social implications of a shift to producing and consuming alternative proteins – for women, smallholders raising livestock and artisanal fishers, for example – have not been well studied. Several studies have suggested that alternative proteins will lead to large increases in employment, but they are silent on where these jobs will be created and where they will be lost. For example, ClimateWorks and Global Methane Hub (2023) report that the scaling of investment in alternative proteins will create up to 83 million jobs by 2050. These numbers are low compared with the traditional livestock sector, which, according to FAO, provides livelihoods for 1.3 billion people, mostly poor livestock herders and smallholder farmers (FAO, 2016). For the employment challenges in HICs, see Verkuijl et al. (2022).

A study of the implications of a growing alternative meat market in the USA concluded that, while it could become a threat to traditional large-scale commercial livestock producers, this was not likely (Newton & Blaustein-Rejto, 2021). Rubio et al. (2020) argue that, if alternative proteins meet the demand for lower-quality meat products (e.g., chicken nuggets), then the demand for luxury meats (e.g., steak) can be met by smaller-scale and more sustainable and humane animal farming methods.

However, IPES-Food (2022) and Howard (2022) have raised concerns about the over-centralisation of control in the alternative protein business, which might reduce competition, worsen existing power asymmetries by reducing organisational diversity, and increase, rather than reduce, the fragility of food systems.

Alternative proteins are a source of quality protein and offer other health advantages, but there are many questions about their nutritional value, health impacts, taste and cost. There are micronutrients and minerals in meat and fish that are not found in alternative proteins, and the various types of alternative protein differ in their nutritional content. Fraeye et al. (2020) suggest that a long trajectory of research needs to accompany these products. A related area that also requires further research involves the costs and sensory attractiveness of alternative proteins vis-à-vis traditional livestock products. Bryant (2022) argues that the development of new ingredients and processing methods could make plant-based proteins tastier, cheaper and healthier. Van Huis & Gasco (2023) and Parodi et al. (2022) suggest that research is needed to confirm that delivering reliable quantities of high-quality and consistent insect meal using cheap organic waste is a safe and cost-effective process. More research is needed into animal welfare and food safety questions surrounding the use of insects as animal feed and human food.

Overall, more comparative research is needed on the costs, nutritional value and attractiveness to consumers of the full range of alternative proteins in multiple contexts and geographies (Onwezen et al., 2021).

3.8 Conclusion

It is clear that there is a need for alternative proteins, but it is not clear whether they will be a substitute for a sizeable share of ASF or will complement it, given the large unmet demand for high-quality proteins in LMICs. Further, there is a lack of clarity regarding the relative nutritional value and environmental footprint of the different types of alternative protein. Processes are still at an early stage of development; over time, their relative benefits and roles in the food system will become clearer. Table 3.3 provides a qualitative, expert judgement of the potential of various technologies discussed in this section with regard to the four criteria of the Agriculture Breakthrough Agenda.

TABLE 3.3 **Qualitative assessments of alternative proteins across the four breakthrough principles**

Type of alternative protein processes	Sustainably increases agricultural productivity and incomes (and improves nutrition)	Reduces greenhouse gas emissions	Safeguards soil, water resources and natural ecosystems	Adapts and builds resilience to climate change
Plant-based	Medium	High	Medium to high	Medium to high
Microbial fermentation-based	Medium to high	Medium	Medium to high	High
Cultivated meat	Medium	Medium	Medium to high	Medium
Insect-based food and feed	Medium to high	Medium	Medium to high	Medium

Source: Authors' qualitative expert judgement based on available evidence presented in Section 3.2. Note that this is not a rigorous evidence synthesis or systematic review-based analysis and, as such, needs to be interpreted with care.

Several (optimistic) exploratory assessments have been undertaken regarding the future market share of alternative proteins: for example, Morach et al. (2022) use market share projections to suggest that, by 2035, 11% of all ASF (meat, seafood, eggs and dairy) consumed globally will be from alternative protein sources, and that this figure would be 22% with additional support from regulators and improved technology. Nearly 1,300 companies are working on alternative proteins worldwide (Thornton et al., 2023), and the cost of a hamburger patty made from cultivated meat has already dropped sharply since the first burger in 2013, which cost USD 325,200 (Bashi et al., 2019), although, as of 2023, prices have not yet reached parity with those for conventional burgers.

These signals suggest that, although alternative proteins account for a very small share of the overall protein market, with plant-based foods and milks accounting for 1% and 15% respectively of the US market (GFI, 2023), for example, this share is set to grow overall. However, for alternative proteins to achieve significant market share, far more effort is required to regulate the sector, reduce the cost of high-quality protein alternatives and create an environment for consumers where the healthiest and most sustainable food options and diets are the easiest to choose.

Regional, national and even local food preferences vary considerably. In some HICs, meat plays a larger role in diets than in many LMICs; indeed, in some countries, such as India, meat plays a relatively small role in most people's diets (although dairy products are important, and the consumption of poultry has been increasing rapidly). Cultural preferences also vary: for example, insect-based food will be more acceptable in some places than in others, and some cultural preferences can help accelerate uptake of some alternative proteins. Therefore, over time, different types of alternative protein might well dominate different markets.

Finally, current trends, especially in HICs, suggest that, rather than being truly transformative and helping reduce consumption of ASF over and above nutritional guidelines, there is a risk that the alternative protein industry is being captured by dominant large-scale firms, for example by purchasing innovative start-ups (Howard, 2022). Policymakers in all countries should take action to maintain a level playing field – through international collaboration on frameworks, regulations and labelling and by lowering entry barriers and transaction costs – and should encourage a competitive market in which new alternative protein firms can flourish in order to achieve improved climate resilience, better nutrition and environmental sustainability.

Close up of marula fruit at a market in South Africa.
Sheona Shackleton / CIFOR

4 Reduce food loss and waste

Core authors: **Douglas Merrey, Aditi Mukherji**

KEY HIGHLIGHTS

- If food loss and waste were a country, it would be the third largest GHG-emitting nation in the world.
- Food is lost or wasted at all stages of the food chain, from production to consumption. Interventions to reduce FLW must be targeted carefully to achieve significant results.
- Reducing food losses at the production and transport stages in LMICs can improve food security significantly as well as reduce GHG emissions; reducing food waste at the retail and consumption stages in HMICs can potentially contribute to reducing GHG emissions.
- To develop appropriate FLW reduction policies, better data on volumes, impacts, benefits and costs are needed at national and international levels.
- Because food systems are complex systems, interventions must be planned and monitored carefully to reduce rebound impacts that may minimise or even negate reductions of GHG emissions.

4.1 The context

Food loss and waste (FLW) is a major challenge for the global food system, with far-reaching implications for GHG emissions, the environment and human wellbeing. "Food loss" occurs before consumption, while "food waste" occurs at the retail and consumer levels (Moraes et al., 2021).

A lifecycle analysis of FLW from the food production and food consumption value chain found that FLW contributed 9.3 billion metric tonnes (MT) of CO^2e emissions in 2017 (Zhu et al., 2023). Poore & Nemecek (2018) put the contribution of food waste to total global GHG emissions at 6% without accounting for on-farm food losses. FLW also has impacts on land, water and other resources. For example, food that is lost and wasted accounts for up to 23–24% of total water, arable land and fertiliser consumption, and in the end is not even available to or used by consumers (Kummu et al., 2012; Lopez Barrera & Hertel, 2021). Food waste that goes to landfills additionally contributes some 3.3 billion MT of CO^2e methane emissions (Lopez Barrera & Hertel, 2021). These numbers are stark. If FLW were a country, it would be the third largest GHG-emitting nation in the world.

FLW occurs throughout the production, processing, distribution and consumption phases of the food value chain. In high- and middle-income countries (HMICs), most food waste is generated by consumers over-purchasing and improper storage and disposal of leftovers, though there are exceptions, where high losses in wealthy countries also happen at production stage (Gooch et al., 2019). A large share of FLW in low-income countries (LICs) comes from losses in the pre- and post-production stages. Globally, over 30% of total food production is lost to human consumption, with 45% of fruits and vegetables, 35% of fish and seafood, 30% of cereals, and 20% each of dairy products and meat and poultry being lost or wasted at various stages of the food value chain (FAO, 2023b). The proportion of food loss and waste is higher in high-income countries (HICs) compared with low- and middle-income countries (LMICs) (Lopez Barrera & Hertel, 2021). Estimates from sub-Saharan Africa show that over 29% (58.8 million MT(Aragie, 2022; Baptista et al., 2022); in China, 27% is lost or wasted (Xue et al., 2021). These percentages are higher in HICs. The total value of FLW globally is estimated to be between USD one trillion and USD 2.5 trillion (Lopez Barrera & Hertel, 2021).

Reducing FLW is considered essential for reducing GHG emissions and improving food security and environmental outcomes (IPCC, 2023a; Durán-Sandoval et al., 2023). Globally, halving FLW production can potentially reduce GHG emissions by 4.65 MT of CO^2–eq annually, representing about 25% of GHG emissions from the global food system in 2017 (Zhu et al., 2023). Springmann et al. (2018) estimated that halving FLW would reduce environmental impacts by 6–16% compared with 2050 baseline projections. Most research notes that reducing FLW, along with a shift from diets high in ASF to more plant-rich diets, can substantially reduce GHG emissions from food systems.

4.2 Strategies for reducing food loss and waste at various phases of the value chain

Food is lost or wasted at four stages in the food value chain: (1) production (including pre-harvest and post-harvest on-farm losses); (2) processing and transport (including transport, processing and packaging technologies and use of by-products); (3) distribution (including food spoilage at the retail stage); and (4) consumption. This section discusses the most important technologies and approaches available for reducing FLW from food value chains. While interventions at specific stages of the food chain are important, food chains are complex systems; therefore, policy and other interventions must be systemic. Interventions at one stage will often have significant, often unintended, impacts at other stages (Kuiper & Cui, 2021; Cattaneo et al., 2021).

4.2.1 Reducing FLW at the production stage

Milk is delivered, filtered and tested in Meru, Kenya, before being sent to the processor.
Georgina Smith / CIAT

Food losses at the production and post-harvest stage are comparatively lower in the Global North than in the Global South, as pest control, production and harvesting technologies are more efficient than those used by smallholders in developing countries. Therefore, targeting the production stage among smallholder farmers in the Global South will have the greatest pay-off. For example, a study of losses in five staple food value chains in six countries found that 60–80% of the total losses occurred at the producer level (including pre-harvest losses). Most product deterioration occurs before harvest, showing the importance of reducing pre-harvest losses (Delgado et al., 2021). Smallholders often store harvested grain and other food for home use over the coming year; losses can be very high.
Therefore, improving post-harvest storage can have major payoffs, as a study of maize storage in Tanzania demonstrates (Brander et al., 2021; Case study 4.1).
Stathers et al. (2020) studied post-harvest interventions across 57 countries in South Asia and sub-Saharan Africa for 22 crops. For grains and legumes, the most effective approaches and practices were timely harvesting, protecting the crop from direct contact with soils, and storage using hermetically sealed containers with a mixture of chemicals. For roots and tubers, piecemeal harvesting, curing and sorting to remove damaged roots, use of digging tools that reduce harvesting damage, improved storage containers and sprout suppressants were most effective. To reduce losses of fruits and vegetables, the most effective technologies were use of maturity indices, gentle handling, removing damaged fruits, and cool or cold storage.
A case study of potatoes in Kenya examined four business models and found that the use of certified seed material combined with mechanisation significantly improved productivity and profitability and reduced food losses and net GHG emissions (Amon et al., 2006; Soethoudt & Castelein, 2021). However, the lack of financial and other services prevents smallholders from adopting these interventions.

4.2.2 Reducing food loss at the processing and transport stage

In the Global North, there is relatively little food lost at the processing and transport stage because of the use of modern packing technologies and the reuse of waste during processing. Losses are highest for fresh fruits and vegetables, followed by dairy and meat products (Axmann et al., 2022). A detailed study of food losses during transport in Poland found that a relatively small amount of food is lost at this stage but recommended stopping the current practice of unconditional disposal of products not delivered at the appropriate time (Lipińska et al., 2019).

The most promising intervention" in the processing and transportation stage are focused on fresh fruits and vegetables, fish, meat and dairy products in the Global South. Improving packaging and storage during transport and supporting fruit processors to increase their capacity to process all that they receive are important interventions (FAO, 2019b). For example, in South and Southeast Asia, FAO promoted the use of nestable plastic crates combined with good post-harvest management practices to transport fresh produce. These crates significantly lowered losses, leading to economic

benefits for wholesalers, retailers, customers and producers: customers got better quality produce with a longer shelf life, while upstream participants profited from having more quality produce to sell (FAO, 2019b).

A detailed field study of post-harvest losses from farmer to retailer in two value chains in Ethiopia for storable staple teff and perishable liquid milk found much lower losses than expected: 2.2–3.3% and 2.1–4.3% of total production. Losses in the emerging modern retail sector, which uses better packaging, refrigeration and handling practices, are on average half the levels found in the traditional retail sector (Minten et al., 2021). These cases suggest that over time, as the transport, wholesale and retail sectors modernise, FLW will decline.

4.2.3 Reducing food loss at the distribution stage, including the retail stage

In the Global North, fruit and vegetable losses are very high at the retail level, largely because retailers often discard products that are not 'perfect' in colour, size or shape. Losses of perishable foods such as fish are also high, even in MICs like Brazil. In the Global South, retail losses can also be high because of poor-quality packaging and temperature and humidity control, mixing different products in a single cold room, and not displaying products carefully (FAO, 2019b).

A systematic review in Europe of the causes of food waste and practices to reduce it at the retail level identified 34 causes and 32 practices aimed at reducing waste; these are affected by multiple agents, not only market management (de Moraes et al., 2020). Solutions identified included more flexible quality standards for fruits and vegetables, diverting surpluses to other channels such as food banks in collaboration with NGOs, flexible pricing and promotion, better management of inventories, better collaboration and data sharing with logistics partners, implementation of waste-reduction operational systems, smaller package sizes, and avoidance of sales that encourage over-purchasing (de Moraes et al., 2020; Schanes et al., 2018). A detailed study of food waste in Swedish supermarkets found that the largest losses are in meat and bread. Separating unsold bread from its packaging and recycling it as animal feed was shown to reduce GHG emissions (Brancoli et al., 2017).

Retailers will respond to price signals. They can be motivated to adopt waste-reduction practices through a combination of tax credits for donated food and high waste disposal fees (Lee & Tongarlak, 2017; FAO, 2019b; World Bank, n.d.; UNEP, 2021). However, there could be potential unintended consequences of such tax and price signals in other parts of the food system. For example, tax credits for donated food may serve as a disincentive to implement other FLW prevention measures (Kinach et al., 2020).

4.2.4 Reducing consumers' food waste

Consumer food waste increases with prosperity (van den Bos Verma et al., 2020). In Europe and the USA, unlike in the Global South, half of all FLW occurs at the consumption stage (FAO, 2019b; Nicastro & Carillo, 2021; W. Dong et al., 2022). An extensive review distils lessons learned on the causes of waste and the effectiveness of various interventions. Tested reduction strategies include education and information campaigns, charging fees for waste disposal, and improving packaging and labelling (Schanes et al., 2018). These interventions also apply to emerging economies (Lopez Barrera & Hertel, 2021).

Makov et al. (2020) studied the effectiveness of a food-sharing app in the UK for reducing food waste. They analysed 170,000 postings over 19 months and found that 90 tonnes of food waste were diverted from disposal, avoiding emissions of 87–156 MT of CO^2e. The results suggest that the sharing economy could contribute to reducing food waste and increasing food security. Composting food waste is

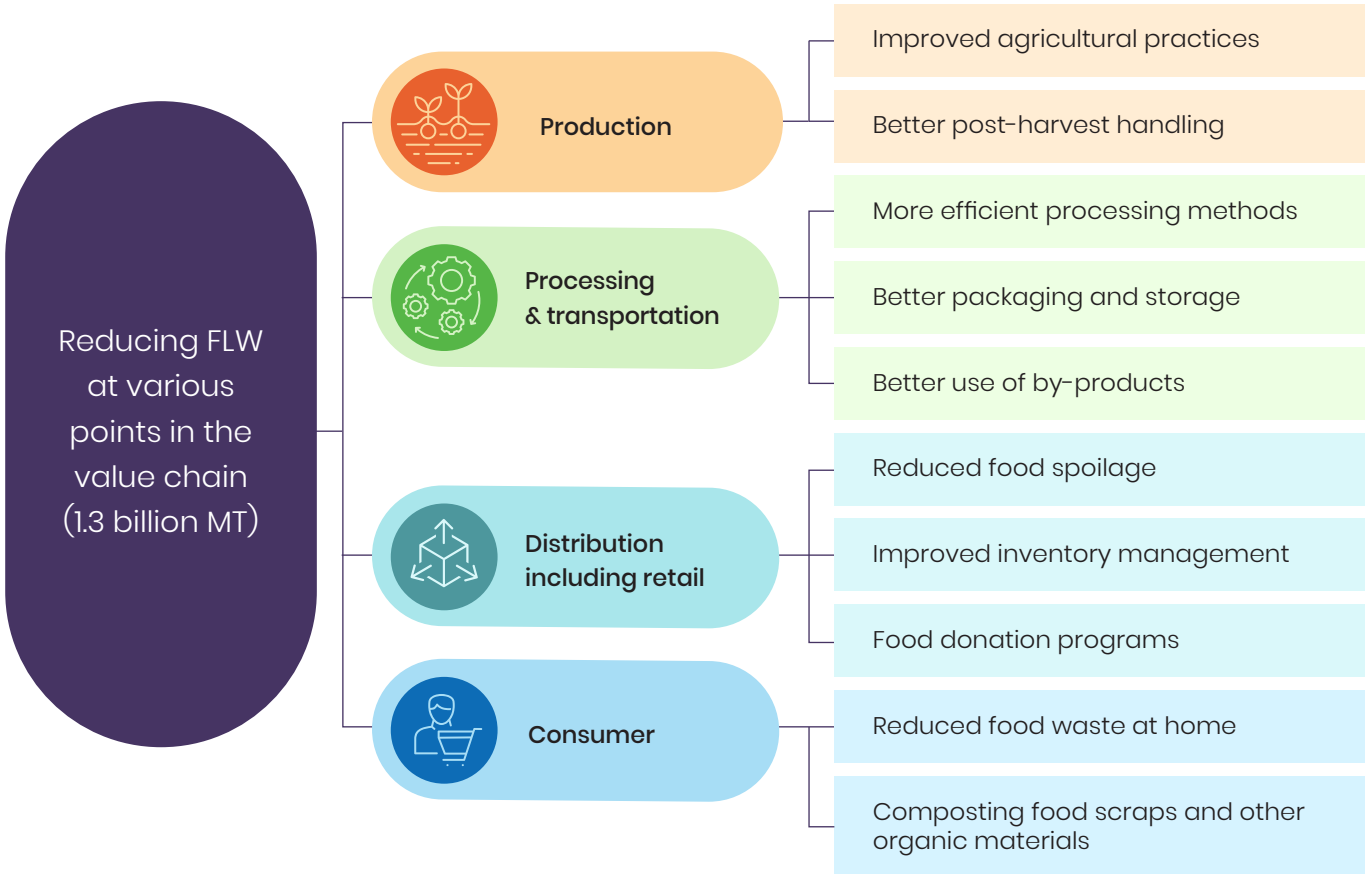
another promising strategy for reducing emissions from waste (Awasthi et al., 2020). Pérez et al. (2023) found in California that composted emissions were 38–84% lower than the equivalent landfill figures, with a potential net minimum saving of 1.4 MT of CO^2e by 2025.

Excess food consumption ('overnutrition') is not usually included in the definition of food waste. Nevertheless, encouraging people to eat healthy diets may help reduce food waste. A study from Italy estimated that 1.553 MT CO^2e/year of excess calories are consumed due to overnutrition compared with the typical diet (6.15 MT CO^2e/year) (Franco et al., 2022). A study in the USA documented a similar level of waste per person, accounting for 7% of crop area (Conrad et al., 2018).

To conclude, there are no universal, one size fits all solutions to reduce FLW. In the Global North, the greatest potential is at the consumer level. In the Global South, the greatest potential is at the production, processing and transportation levels. Figure 4.1 is a visual representation of possible pathways for addressing FLW at various stages of the food value chain.

FIGURE 4.1

Pathways for addressing food loss and waste and emissions at various stages of the food value chain



Source: Authors

CASE STUDY 4.1

Better on-farm storage improves food security in Tanzania

A randomized control trial (RCT) was conducted in Tanzania to test the impact of better on-farm storage on food security. The RCT randomly allocated an inexpensive storage technology, hermetically sealed bags, to a sample of smallholders and monitored those who received the bags and those who did not receive them. The bags had been demonstrated to be effective in preventing losses, especially for grain (in this case, maize). Each household received five bags with the capacity to store 100 kg of grain each, and they received training on how to use the bags. There was no further intervention such as offering credit; the focus of the experiment was to test the impact of the technology itself on household food security. Food insecurity was measured with quarterly rounds of the reduced Coping Strategies Index over 15 months, using SMS-based mobile phone surveys. A self-assessment instrument was used to measure post-harvest losses. The intervention significantly reduced the probability of post-harvest losses and the proportion of losses, and reduced the proportion of severely food-insecure households by an average of 38% in the lean season and by 20% during the full seasonal cycle. The cost of the bags in most sub-Saharan countries is USD 2–2.50 per bag, not insignificant for many rural households. Further research is needed to complement research aimed at improving productivity and sustainability.

Source: Brander et al., 2021

4.3 Metrics for measuring progress

Sustainable Development Goal (SDG) 12 calls for responsible production and consumption. Target 12.3 aims, by 2030, "to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses".

Although limited by insufficient quality data, FAO's (2019b) 'food loss index' and the United Nations Development Programme's (UNEP, 2021) complementary 'food waste index' provide consistent approaches to measuring progress towards achieving the SDG 12.3 target, halving food waste at the consumer and retail levels. The 'food loss index' (SDG target 12.3.1a) measures changes in the percentage of food lost from post-harvest up to but not including the retail and consumer stages. Note that it excludes pre-harvest losses, which can be significant. The 'food waste index' measures the percentage of food lost at the retail and consumer stages (SDG target 12.3.1b). This index focuses on the 10 most valuable commodities within five commodity groups in each country: cereals and pulses; fruits and vegetables; roots, tubers and oil-bearing crops; animal products; and fish and fish products. Three metrics are used by FAO: economic value, caloric units and physical quantities (see also Lopez Barrera & Hertel, 2021), but FAO acknowledges that the economic value measure has serious flaws (FAO, 2019b). FAO reports that globally, estimated food loss slightly increased between 2016 and 2020 from 13% to 13.3%. This corresponds to a food loss index increase from 98.7 to 101.2. Regionally, sub-Saharan Africa has the highest losses at 21.4%. Latin America and the Caribbean, and Europe and North America have the lowest losses at 12.3% and 9.9% respectively.

The United Nations Environment Programme (UNEP, 2021) notes that there are insufficient quality data to develop precise estimates of the level of food wasted at retail, household and food service levels. Globally, UNEP estimates that around 931 MT of food is wasted annually, 61% from households, 26% from food services, and 13% from retail; but as with other measures, these estimates vary widely by region, country and type of food.

Apple Cold Storage, Morocco. Apples placed in cold storage can last more than three months.
Douglas Varchol / CGIAR

4.4 Actors and change agents who can play a role in reducing food loss and waste

Table 4.1 lists potential change agents able to drive progress in reducing FLW. It includes international as well as national and local partners. None of the AIM4C sprints were specifically on reducing food loss and waste. Section 4.6 suggests the potential roles of the most significant change agents.

TABLE 4.1 **Actors who can play a catalytic role in reducing food loss and waste**

Role	Actors who can play a catalytic role in reducing FLW
Long-term vision and action plan	FAO; UNEP; SAVE FOOD: Global Initiative on Food Loss and Waste Reduction (an FAO programme); One Planet's SFS Programme; HLPE-FSN; *MACS-G20 Collaboration Initiative on Food Loss and Waste*
Demand creation and management	National and local governments; food wholesalers and retailers; NGOs
Infrastructure and supply chains	National and local governments; food wholesalers and retailers
Finance and investment	World Bank; regional development banks; IFAD; governments; private sector; foundations (e.g., Bezos Earth Fund)
Research and innovation	Universities and other research institutes, including WFBRI; CGIAR; WRI; commercial food processors; GFAR; FARA; regional agricultural research associations (e.g., CORAF/WECARD; ASARECA; SADC-FANR)
Market structures	National and local governments; WTO
Standards and certification	National governments
Trade conditions	National governments; World Trade Organization

Knowledge, capacity and skills	CGIAR; Clim-Eat; APHLIS; consumer organisations; extension services at farm level; universities; NGOs
Social engagement and impact	Consumer organisations; farmers' organisations; NGOs, research institutes
Landscape coordination	United Nations (e.g., FAO, UNEP, World Food Programme); SAVE FOOD; Committee on World Food Security

Source: Authors
Notes: APHLIS = African Postharvest Losses Information System; ASARECA = Association for Strengthening Agricultural Research in Eastern and Central Africa; CORAF/WECARD = West and Central African Council for Agricultural Research; FARA = Forum for Agricultural Research in Africa; GFAR = Global Forum on Agricultural Research and Innovation; HLPE-FSN = High-Level Panel of Experts on Food Security and Nutrition; SADC-FANR = South African Development Community Food Agriculture and Natural Resources; SFS = Sustainable Food Systems; WFBRI = Wageningen Food and Biobased Research Institute; WTO = World Trade Organization.

4.5 Barriers to implementation

4.5.1 Data uncertainty

A major barrier to developing appropriate FLW reduction policies is the lack of accurate data at national and international levels for each level of each value chain; and the lack of cost and benefit analyses to support effective policymaking (FAO, 2019b; Lopez Barrera & Hertel, 2021). Uncertain data also limit the accuracy of the food loss and food waste indices (FAO, 2019b; UNEP, 2021). Currently available metrics do not measure the loss of food nutrient quality.

4.5.2 Weak incentives and consumer awareness

High producer subsidies are a barrier to reducing FLW as they lower food prices and therefore undermine incentives to reduce waste, especially in HMICs (World Bank, n.d.; FAO, 2019; Lopez Barrera & Hertel, 2021; van den Bos Verma et al., 2020). Consumer education reduces waste, but employed people paradoxically waste more food as they have less time to worry about waste (Schanes et al., 2018). The incentives to reuse unsold food remain weak, especially in HICs.

4.5.3 Insufficient financial support in the Global South

In the Global South, producers' lack of access to the resources needed to adopt improved cultivation and post-harvest storage technologies is a serious barrier to reducing losses, as are poor transport and storage technologies for marketed produce. Improving affordable and accessible financial services, bundled with access to agronomic advice, market information and weather forecasts for smallholders and small businesses, could help reduce this barrier (Soethoudt & Castelein, 2021; Cattaneo et al., 2021). Even in the Global North, opportunities to finance FLW reduction and low carbon diets remain particularly untapped, with only USD 0.1 billion at the project level and USD 1.1 billion at the company level annually tracked to this activity in 2019/20. This represents a minor fraction of annual needs, estimated at USD 48–50 billion (CPI, 2023).

Sacks of maize seed ready for sale at small seed company Bidasem, Celaya, Mexico.
X. Fonseca / CIMMYT

4.6 Recommendations for reducing food loss and waste

4.6.1 Strengthen international collaboration to improve the quality of data at multiple levels

Reliable, timely and comparable data are needed to enable policymakers and other actors to target the optimum opportunities to reduce FLW. A well-funded international programme to fill the data gap, by using existing protocols such as the Food Loss and Waste Protocol co-owned by FAO, WRI, UNEP and others (*https://www.flwprotocol.org/*) is needed. We recommend that FAO, CGIAR, WRI, One Planet and MACS-G20 Collaboration Initiative, among other initiatives, should provide coordinated and increased technical assistance and data to existing multi-stakeholder platforms currently promoting dialogues among researchers, industry, governments and civil society on the needs and means to reduce FLW. One Planet's *Sustainable Food Systems Programme* is a potential international partner, as is the *African Postharvest Losses Information System* (APHLIS). APHLIS collects, analyses and disseminates data on post-harvest losses of cereal grains and legumes and roots and tubers; this includes estimates of the economic and nutritional dimensions of post-harvest loss. APHLIS is also improving the interactive tools for accessing FLW data and expanding its network of African experts. The *Wageningen Food & Biobased Research Institute* (WFBRI), which does applied research to identify sustainable food system innovations, including reducing FLW (Kok et al., 2021), could be of assistance in designing rapid data gathering methods in collaboration with national institutions.

4.6.2 Repurpose agricultural subsidies to incentivise reduction of FLW

Current agricultural subsidies distort prices, reducing incentives for retailers and consumers in HMICs to save food (FAO, 2019b; World Bank, n.d.; Lopez Barrera & Hertel, 2021). We recommend scaling out investments to strengthen access to the financial and information services needed to transform agriculture, particularly in the Global South. Improving production, post-harvest and packaging technologies can result in lower waste and GHG emissions and improve food security (Soethoudt & Castelein, 2021; Minten et al., 2021). We further recommend that the PD, which is co-led by the World Bank and the UK government, should – through roundtables and discussions with policymakers – prioritise the formulation of concrete pathways for repurposing subsidies to incentivise the reduction of FLW as well as fund initiatives to do so, as a part of larger efforts to repurpose harmful agricultural subsidies overall. Action could include international collaborative research/policy dialogue leading to a white paper on repurposing agricultural subsidies overall, with a clear pathway for how FLW-related perverse incentives can be tackled under various policy and socioeconomic contexts.

4.6.3 Strengthen international multi-stakeholder platforms to raise consumer awareness about FLW

Reducing FLW is an integral part of the larger ongoing efforts to transform global food systems to provide healthy and sustainable diets, while also significantly reducing GHG emissions and conserving land and water systems (IEA, 2022; Santeramo & Lamonaca, 2021). We recommend that existing multi-stakeholder partnership platforms such as One Planet's Sustainable Food Systems (SFS) Programme and FAO's SAVE FOOD: Global Initiative on Food Loss and Waste Reduction be further strengthened by the inclusion of other stakeholders such as CGIAR, WRI and private sector food companies. These platforms promote dialogue among researchers, industry and the private sector, politicians and civil society on FLW, and raise public awareness. Other potential partners include CGIAR to support international and local research, and the High-Level Panel of Experts on Food Security and Nutrition (HLPE-FSN), also supported by FAO, to foster dialogue. Table 4.2 sums up the recommendations.

TABLE 4.2 **Recommendations for addressing food loss and waste**

Summary of Recommendations	Relevant partners for implementation	Recommendation applicable at levels		Themes*
		Domestic	International	
Develop a well-funded international programme to fill the data gap, by using existing protocols, with the aim to provide detailed annual estimates of FLW (including data on nutrient losses) along the food supply chain	FAO, UNEP, WRI, APHLIS		✓	Themes 3 and 4
Formulate concrete pathways for repurposing perverse and harmful agricultural subsidies to incentivise and fund efforts for the reduction of FLW, as part of larger efforts to repurpose agricultural subsidies overall	PD, which is co-led by the World Bank and the UK government		✓	Theme 2
Strengthen multi-stakeholder platforms that promote dialogue among researchers, industry and the private sector, politicians and civil society, and raise public awareness on the need and ways and means to reduce FLW	FAO, CGIAR, WRI, One Planet	✓	✓	Themes 2 and 5

Source: Authors
Notes: * Theme 1: Climate finance; Theme 2: Policies, regulations and innovations; Theme 3: Metrics, indicators and standards; Theme 4: Research and development and demonstration (RD&D); Theme 5: Private sector, markets and trade

4.7 Gaps in scientific knowledge

Cattaneo et al. (2021) outlined five research challenges for reducing FLW: (1) measuring and monitoring FLW (Goossens et al., 2019); (2) assessing benefits and costs of FLW reduction; (3) designing FLW reduction policies and interventions; (4) understanding how interactions between value chain stages and across countries affect outcomes of FLW reduction efforts; and (5) preparing for changes in the relative importance of losses and waste as economies develop. Significant knowledge gaps include the paucity of detailed, comparable studies measuring the level, location and causes of FLW, the impacts on food costs and availability, and the benefits and costs of possible interventions (Delgado et al., 2021). Further, a very recent study found that because of the 'rebound effect' of lower FLW, food prices may become cheaper, leading to increased consumption and production, which will significantly reduce the positive impacts on GHG emissions (Hegwood et al., 2023; Bellemare, 2023). This needs further study from a food systems and lifecycle perspective. However, in the overall context of declining growth rates in agricultural productivity due to climate change (IPCC, 2022a), reducing emissions for all sectors, including FLW, remains paramount.

Research is needed on the effects of storage at home, shopping infrastructure, the potential of new technologies such as smart fridges, and the role of food-sharing practices (Schanes et al., 2018; Makov et al., 2020). Future research should explore the FLW–food security–water–energy–food nexus: transforming food systems may contribute more to reducing FLW than direct FLW interventions (Santeramo & Lamonaca, 2021). Finally, research is needed on gender and other socioeconomic equity dimensions of current FLW efforts (Minten et al., 2021). Similarly, not much is known about the impact of FLW on food prices (Kuiper & Cui, 2021).

4.8 Conclusion

FLW is a major contributor to GHG emissions, degradation of water and land resources, and food insecurity. FLW levels vary significantly among crops, countries and value chain stages. Therefore, interventions must be targeted to where the greatest gains are possible. Improving the handling, packaging, transportation and storage of perishable foods is one target. In the Global South, improving pest control, harvesting and household storage offers significant opportunities to reduce losses and improve food security. Losses at the processing and transport stages can be reduced by using better packaging technologies and improving storage and refrigeration facilities.

Targeting retailers and consumers in HICs is a critical path to reducing the impacts of FLW. Retailers can reduce supply chain losses through better inventory management, donating unsold food to food banks, and improving labelling and packaging as well as reducing quality standards/requirements for the shape and colour of fruits and vegetables. Targeting consumers in wealthy countries offers significant opportunities to reduce waste through education and incentives. Table 4.3 summarises the potential global contributions of reducing FLW to climate-resilient sustainable agriculture.

To implement FLW reduction at scale, four barriers must be overcome: (1) improving FLW data; (2) providing effective incentives to conserve food and improve awareness of doing so in the Global North; (3) improving access to financial resources, information and technologies in the Global South; and (4) strengthening international cooperation.

TABLE 4.3 **Qualitative assessments of various ways of reducing food loss and waste across the four breakthrough principles**

Type of alternative protein processes	Sustainably increases agricultural productivity and incomes	Reduces GHG emissions	Safeguards soil, water resources and natural ecosystems	Adapts and builds resilience to climate change
Production (pre- and post-harvest)	High	Medium	Medium to high	High
Processing and transport	Medium	Medium to high	Medium to high	Low to medium
Retail	Low	Low	Low	Low
Consumption	Low	Medium to high	Medium to high	Medium

Source: Author's expert judgement based on available evidence presented in Section 4.2. Note that this is not a rigorous evidence synthesis or systematic review-based analysis and as such, needs to be interpreted with care.

Reducing FLW will require effective international cooperation and significant changes in national policies and the behaviour of everyone, from producers to consumers. This shared responsibility applies to all recommendations. Reducing FLW can contribute significantly to food security and help achieve global GHG emission reduction targets, as well as conserve natural resources and provide a healthy diet to all people.

Trials of drought tolerant beans in Colombia.
Neil Palmer / CIAT

5 Crop and livestock breeding

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KEY HIGHLIGHTS

- Integrating genomic selection, marker-assisted breeding and gene editing into classical breeding programmes can accelerate climate resilience in crop varieties and animal livestock and improve tolerance to both abiotic and biotic stresses.
- Continual improvement of crop varieties for high yield potential without increasing fertiliser requirements, and introgression of nitrogen and water use efficiency using classical and modern tools, can contribute to reduction of GHG emissions.
- Improving animal livestock for production efficiency using genomic selection while ensuring animal health and welfare and crossbreeding of productive breeds with indigenous breeds that have low GHG emissions can be effective in reducing methane emissions.
- There is a need to accelerate research and product development by improving access to technology, intellectual property and genetic resources, addressing governance and increasing infrastructure investments and a focus on breeding orphan and under-utilised crops.
- Crop and animal livestock breeding innovations could be improved by incentivising knowledge sharing and communication among research groups and providing new tools to dissect complex genotype x environment x management interactions that compromise breeding progress.

5.1 The context

Climate change has slowed down the growth in crop yields, reduced livestock productivity and affected the nutritional content of food as well as farm profitability, with major pathways of negative impacts emanating from increasing temperatures, changing precipitation patterns and extreme weather events (IPCC, 2023a; IPCC, 2022b; Rojas-Downing et al., 2017; Lesk et al., 2021; Heino et al., 2023; Rahimi et al., 2021). Crop and livestock breeding is an essential tool for climate resilience and mitigation (Atlin et al., 2017; Bailey-Serres et al., 2019). Breeding crops that can withstand elevated heat, drought, flooding, salinity and other climate stresses can help farmers continue to produce food in a changing climate (Langridge et al., 2021; Cassandro, 2020; Cooper & Messina, 2023), while crop varieties that use water or fertilisers more efficiently and livestock breeds that emit less methane (CH_4) can help in reducing absolute emissions, or reduce emissions intensity (Hickey et al., 2022; Pinares-Patiño et al., 2021; Lammerts van Bueren & Struik, 2017; Goopy, 2019).

In the past, plant breeding was successful in delivering a host of high-yielding varieties that are in use today; however, the rate of genetic improvement must be doubled to meet the future demands (Voss-Fels et al., 2019). For example, annual population growth rate in sub-Saharan Africa is over 2.5%, yet the rate of annual realised genetic gains lags at less than 1.5% per year for most crops in the smallholder farming sector. Therefore, accelerated breeding programmes are essential in the production of crops and livestock that can withstand the impacts of climate change (Born et al., 2021; Ramirez Villegas et al., 2020). This can be achieved by selecting traits such as drought, heat and flood tolerance, and disease resistance. These traits should be integrated in farmer-preferred and productive varieties to ensure their adoption by farmers. There exist several approaches for breeding climate resilient crops, such as classical or traditional breeding, marker-assisted breeding, genomic selection, gene editing, transgenic breeding, with or without participatory processes with end users (farmers) (Ashraf, 2010; Zolkin et al., 2021; Langridge & Reynolds, 2015; Luo et al., 2023; de Sousa et al., 2021). Pre-breeding process is required to discover and then deploy climate-resilient traits in breeding pipelines. An effective approach is to select traits that are inherent in wild or landrace varieties, such as the naturally heat-resistant traits in certain crops (Venkateshwarlu et al., 2022). Another approach involves utilising genetic advancements to introduce novel traits – for example, creating transgenic rice, wheat and barley to improve NUE (Tiong et al., 2021). Crops bred for climate resilience can maintain stable yields even when subjected to certain levels of water-stressed conditions, extreme temperatures and emerging pest and disease pressures. Successful examples include maize varieties bred for multiple traits ranging from heat tolerance and maize lethal necrosis (MLN) to fall armyworm resistance, and their deployment in sub-Saharan Africa. Similarly, developing livestock breeds that are better adapted to heat, drought and other climate hazards can help to ensure the continued production of meat, milk and other animal products under climate stress (Proudfoot et al., 2020). However, it is important to acknowledge that there are limits to any form of adaptation, including adaptation through breeding, where crop and livestock breeds may not work as well under very high temperature levels. This makes absolute reductions in GHG from all sectors, including the agriculture sector, a priority action (Rosenzweig et al., 2020; IPCC, 2023a).

Crop and livestock breeding can also be effective instruments for reducing crop and livestock-related emissions. For example, breeding for crops that are water efficient can reduce the amount of water used for irrigation, thereby reducing GHG emissions by reducing the need to draw water from aquifers or surface water sources (Ćalić et al., 2022). Crop-breeding programmes which target traits that improve NUE can limit nitrous oxide emissions and reduce the need for synthetic fertilisers (Cormier et al., 2016). This includes current breeding efforts to improve various crops including maize for

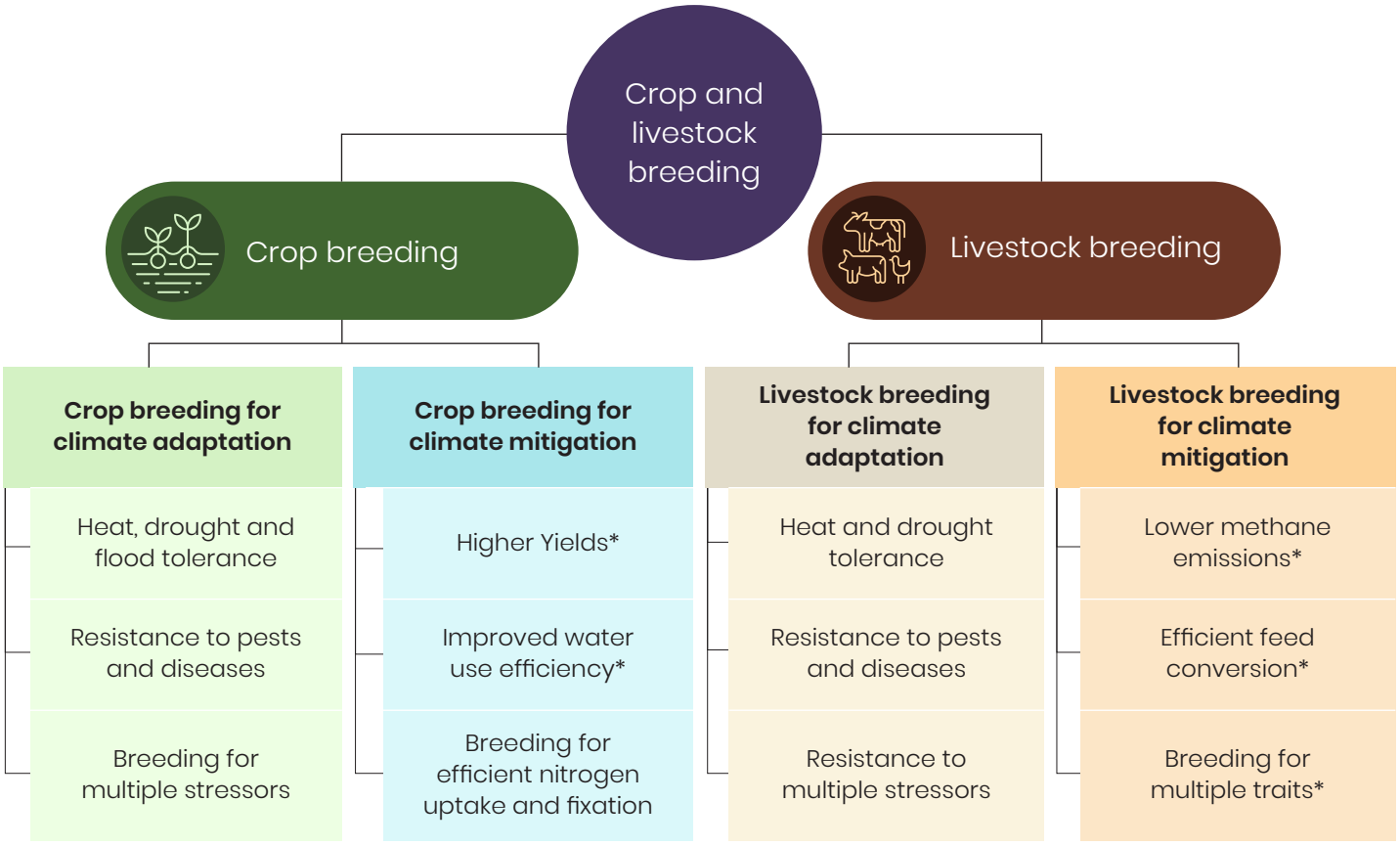
adaptation to low nitrogen fertiliser management and adapting rice varieties to grow with less water (non-flooded) under direct seeded conditions. Current investments in breeding productive leguminous crop varieties with elevated levels of biological soil nitrogen fixation, such as soybean varieties that can be utilised in crop rotations with cereal crops, would significantly reduce the application of nitrogen fertiliser. Increased plant NUE contributes to a reduced land-use footprint, especially when local feed resources are used. Breeding animals that require less forage to produce the same amount of meat and milk can also reduce GHG emissions (de Haas et al., 2021). As ruminant livestock are significant CH_4 producers, breeding for enhanced feed conversion efficiency can also help reduce CH_4 emissions per unit of product (Wallén et al., 2017). Animal breeders should consider the health and welfare of the animals in selection programmes. The unintended consequences and trade-offs for animal welfare and health should be mitigated to prevent reduction in animal fitness because of selection for high productivity traits (European Commission, 2016; van Marle-Köster & Visser, 2021) suggested the use of genomic tools to select against genetic defects alongside good management. For more information on other technologies for reducing CH_4 emissions, see Section 6.

5.2 Strategies and approaches for crop and livestock breeding

There are several ways in which breeders are working to make crops and livestock more resilient to climate change. Figure 5.1 classifies these based on the purpose of the breeding, which can be either climate adaptation – that is, enhancing resilience to various climatic extremes and shocks – or climate mitigation. The latter involves reducing GHG emissions (either absolute or relative) through measures such as increased yields (which translates to less land needed for farming, and hence less deforestation); improved nitrogen and water use efficiencies (to reduce the total amount of fertiliser or water needed for crops); reduced enteric CH_4 emissions, or better feed to produce conversions in animals. Most often, though not always, mitigation through breeding also has adaptation co-benefits (Rosenzweig et al., 2020).

FIGURE 5.1

Pathways for increasing climate resilience and mitigation co-benefits through crop and livestock breeding



Source: Authors

* Breeding that focuses on reducing emissions also has co-benefits for climate adaptation.

5.2.1 Crop breeding for climate resilience

5.2.1.1 Breeding crops for drought, heat and flood tolerance

Incorporating drought tolerance in cultivars is a complex process (Mohammadi, 2018) and is made even more challenging by the diverse target population of environments and the simultaneous effects of abiotic stresses, such as high temperatures, sunlight and inadequate nutritional levels on yield (Cooper & Messina, 2023; Mohammadi, 2018). This has led to a slower than expected pace in developing drought-tolerant varieties. Further, there are trade-offs between drought tolerance mechanisms and mechanisms for higher yields, making it even more difficult to develop effective drought-tolerant crops without these resulting in high-yield penalties (Griffiths & Paul, 2017). Classical breeding approaches have been effective for improving both productivity and the tolerance of crop varieties to abiotic stress. The process can be accelerated by integrating modern tools into classical breeding programmes that emphasise selection for high productivity under abiotic stress conditions such as drought and heat. Researchers have identified genes important for drought-resistant crops through genomic technology and breeding techniques for some selected crops (Dubey et al., 2019). Marker-assisted breeding has facilitated the identification and prioritisation of advantageous features for drought resistance in selected crops (Ashraf, 2010). CGIAR Centers are involved in research on drought-tolerant varieties in wheat (El Gataa et al., 2022), rice (Fonta et al., 2022; Venkateshwarlu et al., 2022) and maize (Musimwa et al., 2022), with several drought-tolerant varieties already released or in the pipeline. To reduce the negative impacts of droughts on crop production, it is necessary to combine knowledge systems and approaches from various plant sciences fields, such as breeding, genetics, genomics, phenomics and appropriate agronomic practices (Mwadzingeni et al., 2016).

Heat extremes significantly impact plants, causing decreased biomass production and reduced flower and fruit production. These disturbances disrupt biological processes such as growth, development, metabolism and gene expression, affecting crop growth and yields (Chaudhary et al., 2020). New scientific developments involve sequencing crop genomes and evaluating ribonucleic acid molecules derived from those genes to assess their response to abiotic stress, including heat stress (Devasirvatham et al., 2016). In particular, large genetic variation in traits that are are associated with high productivity under high temperatures, increases the chances of extracting cultivars which can resist heat stress impacts (Driedonks et al., 2016). Screening studies have successfully identified heat-tolerant and heat-sensitive genotypes using traits related to shoots, flowers, fruits and seeds. This has led to the release of heat-tolerant cultivars like chickpea (Chaudhary et al., 2020) and rice (Senguttuvel et al., 2021). Incorporating heat tolerance traits into genotypes that are high yielding but susceptible to heat stress can improve their thermotolerance. However, heat tolerance gains are limited by narrow genetic diversity, so utilising wild relatives and landraces in breeding can increase useful genetic diversity in crops (Driedonks et al., 2016).

Yield penalties due to water logging and flooding are projected to increase in a warmer world (Liu et al., 2021). Breeding crops for flood tolerance involves incorporating submergence genes into high-yielding popular varieties without reducing their yield potential under non-submergence conditions. This has been done successfully for many rice cultivars (Dar et al., 2018).

5.2.1.2 Breeding crops for resistance to pests and diseases

An increase in the virulence of pests and diseases in a warming world, coupled with indiscriminate use of pesticides, has led to more pest attacks, as well as resistance to conventional methods of pest control, making breeding for resistance to pests and diseases an attractive alternative (Luo et al., 2023; Ashkani et al., 2015). Molecular breeding techniques involving DNA markers like quantitative trait loci (QTL) mapping, marker-aided selection, gene pyramiding, allele mining and genetic transformation have been used to develop resistant rice cultivars by incorporating multiple genes for more durable blast resistance (Ashkani et al., 2015). Similar molecular marker-assisted breeding has been used in wheat to breed cultivars that can combat fungal diseases and herbivorous insects, but there remain significant challenges (Luo et al., 2023).

5.2.1.3 Breeding crops for multiple stresses

Climate change is leading to multiple hazards which occur simultaneously or in close succession (e.g., storm surges leading to floods and salinity ingression; heat stress combined with drought effects; or prolonged droughts followed by extreme rainfall events), leading to compound hazards. As a result, it is becoming necessary to breed crops that can withstand multiple hazards (Lopes et al., 2015). CIMMYT's genetic pipeline for tropical maize in Eastern Africa successfully implemented marker-assisted forward-breeding to develop cultivars with resistance to key diseases and drought tolerance (Prasanna et al., 2021; Prasanna et al., 2022). Similarly, varieties that are tolerant to drought and low phosphorus (Roy et al., 2021), drought-tolerant varieties and those that are resistant to bacterial leaf-blight and blasts, have been identified for rice (Singh et al., 2021). Yet several challenges remain, requiring multidisciplinary collaborations.

5.2.2 Crop breeding for climate mitigation

The conventional approach of breeding for higher yields (Tokatlidis, 2017) contributes to climate mitigation if it translates to lesser deforestation for agricultural purposes. Additional gains in reducing GHG emissions could be achieved by selecting crop varieties that use less chemical fertiliser and irrigation to attain their full yield potential. There are now increasing efforts to incorporate features that help certain crops to improve their nitrogen uptake from the soil, requiring less application of fertilisers, and to make them more water efficient, requiring less irrigation water. Continually improving crop varieties for high-yield potential without increasing their fertiliser requirements would contribute to a reduction of GHG emissions (Riedesel et al., 2022).

A community-based seed producer in Kiboko, Kenya, planted KDV-1, a drought tolerant (DT) seed maize variety.
Anne Wangalachi / CIMMYT.

Many commonly grown crops already have enough genetic variation to increase NUE, but for genetic breakthroughs to be achieved, it is necessary to combine agronomy, crop physiology and effective selection procedures.(Lammerts van Bueren & Struik, 2017). Discriminative NUE traits express themselves better under low-input conditions than under high-input conditions; thus, testing under both low- and high-input conditions can yield cultivars that are adapted to low-input conditions but also respond to high-input conditions (Lammerts van Bueren & Struik, 2017). However, because of the significant genotype-by-environment interaction and the complicated nitrogen behaviour in the cropping system (Sandhu et al., 2021), obtaining these advantages is difficult. There are potentially unforeseen consequences of transgenic plants with altered nitrogen metabolism, such as early blooming, which is currently understudied (Lebedev et al., 2021). Given the urgency of climate change and growing global fertiliser prices, breeding programmes must address NUE more efficiently than is presently being done (Cormier et al., 2016).

Enhancing crop productivity in conditions of limited water availability is of paramount importance for achieving sustainable food production in a changing climate. This necessitates the identification and characterisation of the fundamental genetic and physiological mechanisms that are implicated in the processes of water absorption and transpiration. The molecular breeding programmes prioritise genes that regulate root traits and stomatal development due to their significant influence on water use efficiency (WUE) (Ruggiero et al., 2017; Farooq et al., 2019). To enhance the WUE, it is recommended that plants optimise their water transpiration by means of developing deeper roots and exhibiting early crop vigour. Furthermore, a higher biomass per unit water transpired can be accomplished by means of diverse characteristics, such as photosynthetic biochemistry, responsiveness or greater mesophyll conductance (Condon, 2020).

5.2.3 Livestock breeding for climate resilience and mitigation

By 2050, it is projected that there may be a 70% rise in the demand for animal-based food items globally, necessitating the use of cutting-edge techniques and technology to raise the genetic quality of livestock (Georges et al., 2018). Over the past decade, genomic selection has doubled genetic progress in some major livestock species, particularly in developed countries and in industrial livestock production, but further improvements are needed. In comparison to the commercial livestock industry, vast livestock systems in marginal areas have received less attention. In addition to classical approaches that exploit quantitative inheritance, genome editing provides the opportunity to transfer features between breeds without affecting current production or to create novel phenotypes to address climate-sensitive constraints such as vector-borne diseases (Wilkes et al., 2017a). However, such approaches require increased effort to identify and understand genome variants linked to resilience so that they can be used to drive improved performance in the face of the new biotic and abiotic demands brought by climate change. Novel approaches to breed improvement in partnership with national breeding programmes, which take advantage of informatics tools to gather real-world performance data together with genomic selection, have already demonstrated their potential to improve productivity and have a positive impact in developing countries (Mrode et al., 2020; Ojango et al., 2021).

Livestock enteric methane emissions contribute to anthropogenic GHG emissions. Breeding animals to take advantage of variations in natural CH_4 emissions (Lassen & Difford, 2020) is a demonstrated mitigation strategy that is currently being implemented in the New Zealand sheep industry. This strategy has proven economic advantages, and so far, no negative genetic correlations between low CH_4 emission traits and other desirable traits have been found (Rowe et al., 2022; Hickey et al., 2022). Unfortunately, given the likely specificity of low CH_4 emission trait to production systems, these resources cannot be universally used. In the meantime, the management and dietary measures to decrease emissions in this setting, especially for developing economies, will have the biggest and most immediate impact at the lowest cost (Manzanilla-Pech et al., 2021; Goopy, 2019; de Haas et al., 2021). However, there is growing evidence that under prevailing environmental conditions, indigenous breeds are lower emitters of CH_4 (absolute and per unit of intake bases) than their crossbred or exotic counterparts (Mwangi et al., 2023) per product unit. So, the lower emissions of indigenous breeds and their tolerance/resistance to stress factors (enhanced by climate change) (Baker et al., 1998) should be used as first line resources to address climate change mitigation and adaptation.

In addition, selecting for traits associated with low emissions has been shown to have a major impact on the mitigation of climate change. Improvements in fertility lead to a reduction in the number of replacement heifers and consequently reduce emissions (Bell et al., 2012). About a four-fold increase in milk yield has been reported in the USA between 1945 and 2015, and Cole et al. (2023) estimated that about 50% of this gain was due to genetic improvement. Consequently, the carbon footprint per billion litres of milk produced in the USA in 2007 was only 37% of that in 1944. In developing countries, improving productivity provides a major opportunity for mitigation, while recognising that absolute reductions in global GHG emissions are needed. Recent studies have shown that continuous improvement of animals for production efficiency alongside improvements in management practices reduced gas emissions (Liu et al., 2021). However, breeding livestock for higher productivity or lower GHG emissions could have adverse impacts on animal welfare and health; hence, mitigation strategies should be employed during selection. For example, selection for fast-growing and low-methane-emitting chickens could compromise their health. It was reported by Rayner et al. (2020) that slow-growing broilers were healthier and expressed more behavioural indicators of positive welfare.

5.3 Metrics for measuring progress

Metrics and indicators are crucial for measuring progress in crop and livestock breeding for climate resilience. Clear and quantifiable objectives help policymakers, academics and stakeholders evaluate breeding programmes, measure progress and manage climate change. The key metrics are rates of genetic gain, rates of adoption disaggregated by farmers' gender, wealth and other critical social dimensions, and rates of turnover of varieties in farmers' fields. Historically, genetic gain has focused on measurement of yield, but it has a wider definition that can encompass yield performance under varying climatic conditions, and can also consider non-yield traits such as WUE, NUE, nutritional quality, GHG mitigation and other climate-relevant traits. Genetic gain can be measured on-farm to ensure relevance to real farming systems. Genetic gain is also measured agaist a combination of traits depending on the selection index for the target market segments. Adoption rates provide valuable information on the use of improved varieties and additionally provide a good proxy indicator for the ultimate positive impacts at scale on climate change and farmer welfare (e.g. income, nutrition, labour), including differential effects on women and men. In addition to adoption rates, the rate of turnover of varieties in farmers' fields is an increasingly important metric, as climatic changes at the local level accelerate the need to replace and update varieties in response to emergent climate-related conditions (e.g., length of growing season, pest and disease prevalence). The weighted average varietal age (WAVA) in farmers' fields is now an established metric. Measurement is via new tools such as VarScout, now in early roll-out in countries like Ethiopia and Mozambique, which links variety data collected in the field using mobile phones with a global analytic function. Regional or national objectives customised to specific agroecological zones and socioeconomic situations can also make measuring progress easier. Collaboration among research institutes, agricultural organisations and regional or national multi-stakeholder platforms can inform these aims and develop shared metrics and indicators for tracking progress.

Livestock market. Work with farmers through community-based organizations in the Nyando area of Kenya to find more climate-resilient ways of farming.
C. de Bode / CGIAR

5.4 Actors and change agents in crop and livestock-breeding landscape

Table 5.1 lists potential change agents and actors in the crop and livestocking breeding landscape. It includes international as well as national and local partners. Section 5.6 suggests the potential roles of the most significant change agents.

FIGURE 5.1 **Actors and change agents in crop and livestock breeding landscape**

Role	Crop and livestock breeding
Long-term vision and action plan	CGIAR and its Centers that undertake crop and livestock breeding (Africa Rice, Alliance of Bioversity International and CIAT, CIMMYT, CIP, ICARDA, IITA, ILRI, IRRI); Global Crop Diversity Trust; FAO; Convention on Biological Diversity (CBD); NARES
Demand creation and management	Farmers' and producers' associations such as: PAFO (Pan African Farmers Organization and its member bodies); National Farmers Union (NFU) – United States; Confederation of Farmers Associations of India (CFAI); Confédération Paysanne – France; National Farmers Federation – Australia NARES such as KALRO in Kenya, ICAR in India, EMBRAPA in Brazil, and regional research bodies such as FARA National regulatory agencies – e.g., USDA Private sector: seed and agri-advisory companies
Infrastructure and supply chains	Private sector: Bayer, Syngenta, Corteva Agriscience, BASF Public germplasm banks and repositories: CGIAR's Genebank; United States National Plant Germplasm System (NPGS); Nordic Genetic Resource Center (NordGen), etc.
Finance and investment	Global Climate Fund, World Bank, BMGF, Bezos Earth Fund, various private foundations; bilateral funding by governments
Research and innovation	CGIAR Centers; various agricultural research institutions, e.g., CSIRO, CIRAD, Wageningen University, Swedish University of Agricultural Sciences (SLU); NARES in Global South countries
Market structures	Farmers' cooperatives under national laws, various agribusiness corporations
Standard and certifications	ISO; Global GAP certification; Organic certifiers (e.g., USDA Organic, European Union Organic); Rainforest Alliance – Sustainable Agriculture Certification; GFSI; ISTA
Trade conditions	WTO, relevant treaties and agreements on biodiversity
Knowledge, capacity and skills	CGIAR Centers; various agricultural research institutions, e.g., CIRAD, CSIRO, Wageningen University, SLU; NARES in Global South countries
Social engagement and impact	National and international NGOs that work in the agriculture space
Landscape coordination	CGIAR, FAO

Source: Authors

Notes: BMGF = Bill & Melinda Gates Foundation; CIAT = International Center for Tropical Agriculture; CIP = International Potato Center; CIRAD = French Agricultural Research Centre for International Development; CSIRO = Commonwealth Scientific and Industrial Research Organisation; EMBRAPA = Brazilian Agricultural Research Corporation; FARA = Forum for Agricultural Research in Africa; GAP = Good Agricultural Practice; GFSI = Global Food Safety Initiative; ICAR = Indian Council of Agricultural Research; ICARDA = International Center for Agricultural Research in Dry Areas; ILRI = International Livestock Research Institute; IRRI = International Rice Research Institute; ISTA = International Seed Testing Association; KALRO = Kenya Agricultural and Livestock Research Organization.

A goat on the farm at Nyando, Kenya
C. de Bode / CGIAR

5.5 Barriers to implementation

While there have been a number of advances in the science and technology of breeding, supported by policies and institutions, there remains a number of barriers that prevent uptake of breeding advances, particularly in the LMIC countries of the Global South.

5.5.1 Limited access to advanced technologies and genetic resources

There is limited access to advanced technologies for breeding and genetic resource pools, particularly in low-income countries. In addition, utilisation of high-cost technologies, such as genomic selection and marker-assisted breeding, may be financially expensive for breeders in low-income countries. Limited availability of varied and weather-resistant germplasm collections, including unavailability of elite germplasm that possesses desired traits, such as drought tolerance or heat resistance, is a barrier. Given the long generation time of livestock compared with crops, interventions such as genome editing have dramatically greater potential than conventional breeding strategies. However, the ability to use such methods is severely constrained by lack of understanding of the genetic basis of traits such as disease resistance and tolerance to heat and drought, and research effort is needed in these basic enabling disciplines. Besides the lack of knowledge, gene editing is not suited to improving polygenic traits, which are the majority of relevant traits in livestock. This indicates that the breeder could exploit opportunities to transfer genetic gain from other populations and utilise heterosis and combination effects by crossbreeding of local breeds with highly productive breeds, assisted by modern reproductive biotechnology. In addition, potential risks and pitfalls for animal welfare and health will need to be avoided.

5.5.2 Regulatory constraints and Intellectual Property Rights (IPR)

Scaling-up of breeding activities is significantly hampered by regulatory restrictions and IPR. Even when they have completed thorough safety evaluations, climate-resilient crop types may not be able to be developed or released due to severe rules around genetically modified organisms (GMOs). The use of genetically modified crops with features that increase resiliency to climate change may be hampered by lengthy and expensive approval procedures. Additionally, genetic resource IPR may restrict their availability for breeding programmes, impeding the creation and spread of climate resilient seeds

and breeds. To date, governments have not had a coordinated approach to regulating gene-edited products (FAO, 2022b).

5.5.3 Limited infrastructure and extension services

Upscaling breeding for climate resilience is hampered by a lack of suitable infrastructure and extension services. The effective creation and assessment of novel cultivars can be hampered by inadequate testing fields, breeding nurseries and laboratories. Additionally, farmers' adoption of climate-resilient varieties is hampered by their limited access to extension services and technical skills, which hinders the transmission of breeding technologies and information. For instance, the adoption of better cattle breeds with increased tolerance to climatic stresses is constrained in many developing countries by a lack of effective extension services and information networks.

5.5.4 Governance-related constraints

The prioritisation and adoption of climate-resilient cultivars are constrained by market demand, consumer preferences, and legislative and governance barriers. Inadequate regulatory frameworks supporting climate-resilient agriculture, limited investment in breeding programmes and a lack of commercial incentives for farmers to adopt improved varieties can impede development. To overcome these obstacles, governmental interventions are needed that foster breeding, reward farmers and encourage the use of agricultural and livestock varieties that are climate-resilient.

5.5.5 Inadequate finance and investments in breeding

Breeding programmes with advanced technologies and extensive field testing are expensive. Breeding initiatives and other agricultural research and development have been underfunded in many countries, particularly developing countries, and funding of international agricultural research organisations like the CGIAR has also seen a consistent decline since the early 2000s (Alston et al., 2021; Rao et al., 2019). Lack of government financing hinders research, creation and distribution to farmers. Private investments for breeding operations are crucial. Breeding programmes are long term, and climate change risks may deter private investment.

5.6 Recommendations for scaling up crop and livestock breeding

5.6.1 Strengthen international collaboration for RD&D on crop and livestock breeding through enhanced funding

International collaboration and open knowledge exchange has been a key approach through which crop breeding has been undertaken so far, and such collaborations needs to be strengthened further, as many of these breeding programmes have become incapacitated or diminished over the years due to limited funding. We recommend that existing international collaborations on crop and livestock breeding be further strengthened through enhanced funding support, which could be derived from repurposing of agricultural subsidies, and the PD can play a convening role and commission a white paper on concrete pathways to repurpose agricultural subsidies to flow into genetic innovations. International financial institutions like the World Bank mobilise climate-smart breeding funds through loans, grants and technical assistance. The African Development Bank and the Asian Development Bank sponsor breeding programmes in addition to climate-smart agriculture. Foundations such as the Bill & Melinda Gates Foundation (BMGF) and Bezos Fund have been supporting crop- and livestock-breeding programmes, including those of the CGIAR. Public private partnerships (PPPs) can help raise money for climate-smart breeding, share risks and benefits, encourage innovation and disseminate climate-smart breeding methods and technologies.

CGIAR has been a successful example of such an international collaboration that has served the interests of the smallholder farmers in the Global South (Byerlee & Dubin, 2009; Alston et al., 2021). Other initiatives include the Global Crop Trust and regional initiatives like the West Africa Agricultural Productivity Program (WAAPP) and the Asia-Pacific Association of Agricultural Research Institutions (APAARI). Other partnerships include the Forum for Agricultural Research in Africa (FARA) and the Global Forum on Agricultural Research and Innovation (GFAR). These networks enhance collaboration, exchange best practices and facilitate the adaptation and dissemination of climate-resilient crop-breeding technologies and practices across diverse agroecological zones. Existing global treaties and agreements (Section 5.6.3) further help strengthen international collaborations by laying down the rules of the game. Specific actions for such strengthened global collaboration need to focus on the improvement of neglected orphan crops that contain important traits for climate resilience.

5.6.2 Support RD&D and genetic research protocols through strengthening existing international treaties and focusing on new and emerging challenges

Crop genetic resources make up a "new" global common that is defined by a variety of activities carried out by farmers, gene banks, public and commercial research and development organisations, and regulatory bodies. The United Nations Convention on Biological Diversity (and the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from Their Utilization) and the FAO's International Treaty for Plant Genetic Resources for Food and Agriculture have well laid-out clauses and provisions for accessing benefit sharing for biological resources (Lawson et al., 2019). International organisations, such as the International Union for the Protection of New Varieties of Plants (UPOV) and the Codex Alimentarius Commission set up by WHO and the FAO, play a significant role in developing and harmonising breeding standards and therefore governing the global genetic resources commons. Communities, particularly indigenous communities, have rights and interests under these treaties to be acknowledged as local socioecological system managers, to access genetic resources from other communities and to restrict access to resources that are managed by the community (Halewood et al., 2021). While international collaborations are well established, new needs have emerged in view of climate change. For example, a data-driven decentralised strategy that incorporates crop science, farmers' expertise and environmental needs is needed for development of future climate-resilient breeds (de Sousa et al., 2021). We recommend that existing international collaborations be further strengthened to focus on these new needs, such as development of participatory protocols, including biocultural community protocols for future breeding for climate resilience. CGIAR and/or FAO can play a convening role in this regard.

5.6.3 Accelerate innovations in breeding through knowledge sharing and collaboration among existing platforms

Enhancing research and development (R&D) initiatives is vital to advancing climate resilience in breeding crops and animals. Governments, donors, academic institutions and the corporate sector must all support increased R&D spending to help create cutting-edge breeding techniques for climate resilience. Grand Challenges in Global Agriculture, an initiative of the BMGF, supports multidisciplinary research initiatives tackling significant issues in agriculture, such as climate change adaptation. The Horizon 2020 programme of the European Commission promotes R&D in climate-smart agriculture by providing financing for research projects with a climate-smart agricultural focus. National research organisations and agricultural universities, including several CGIAR Centers, provide major contributions to R&D in crop breeding. The International Livestock Research Institute (ILRI) is the CGIAR Center that contributes to livestock breeding. R&D activities are greatly aided by collaborative research

networks and consortia like the Global Crop Improvement Network (GCIN) and the African Orphan Crops Consortium (AOCC). Global innovation sprints by AIM4C are another innovative way of fostering cooperation and encouraging collaborations for R&D. We recommend that knowledge-sharing platforms be created that connect these various initiatives and widely share innovations. The CGIAR can lead such a platform. Table 5.2 sums up the recommendations.

TABLE 5.2 **Recommendations for crop and livestock breeding**

Summary of Recommendations	Relevant partners for implementation	Recommendation applicable at levels		Themes*
		Domestic	International	
Strengthen existing international collaborations on crop and livestock breeding through enhanced funding support, which could be derived from repurposing of agricultural subsidies	The PD to commission white paper on repurposing subsidies, in collaboration with CGIAR, the Global Crop Trust, WAAPP, APARI, FARA and GFAR		✓	Themes 1 and 2
Strengthen existing international collaborations to focus of new RD&D needs such as development of participatory protocols, including biocultural community protocols for future breeding for climate resilience	The CGIAR, FAO, UPOV and the Codex Alimentarius Commission set up by WHO and FAO		✓	Themes 3 and 4
Create knowledge-sharing platforms that connect these various initiatives that fund genetic innovations and widely share those innovations for further uptake, including by private sector	CGIAR, BMGF, the Horizon 2020 programme, GCIN and AOCC		✓	Themes 4 and 5

Source: Authors
Notes: * Theme 1: Climate finance; Theme 2: Policies, regulations and innovations; Theme 3: Metrics, indicators and standards; Theme 4: Research and development and demonstration (RD&D); Theme 5: Private sector, markets and trade

5.7 Gaps in scientific knowledge

Crop-breeding research often overlooks orphan or under-utilised crops, also known as minor crops, which have the potential to contribute to food security, nutrition and climate resilience (Mabhaudhi et al., 2019) These plants have unique genetic features, are suited to specific local settings and can help tackle challenges like climate change. Neglecting orphan or under-utilised crops is a missed opportunity to improve agricultural biodiversity, increase resilience to climate change and promote sustainable agriculture. These crops offer features like drought tolerance, pest and disease resistance, and nutritional qualities that aid in climate adaptation and nutrition security. There are some attempts to develop improved varieties for orphan crops – e.g., fonio millet (Abrouk et al., 2020); lablab – a legume native to Africa (Njaci et al., 2023); and rice bean in Asia (Guan et al., 2022) – but overall progress is slow when compared with major crops (Kamenya et al., 2021).

Numerous genes and complex interactions with the environment control crucial agronomic and climate-related properties of crops and livestock. Understanding these connections is crucial for successful breeding, especially in especially in livestock, which have long generation times and therefore are slow to respond to conventional breeding approaches. Advancements in techniques like genome-wide association studies (GWAS), genomic selection and multi-environment trials aid in identification and characterisation of complex trait variations (Sinha et al., 2021). However, more research is needed to understand the underlying genetic mechanisms and their interactions with environmental factors (Egea-Gilabert et al., 2021). Similarly, advances in genomics and phenomics are delivering insights into the complex biological mechanisms that underlie plant functions in response to environmental perturbations. However, linking genotype to phenotype remains a challenge, hampering the optimal application of high-throughput genomics and phenomics to advanced breeding (Basavaraj & Rane, 2020). Assimilation of large amounts of data into biologically meaningful interpretations is critical for success (Harfouche et al., 2019). Most important traits are quantitatively inherited and influenced by large genotype-by-environment interactions, which reduces heritability. There is a significant knowledge gap in understanding the complex genotype x environment x management (GxExM) in both crop and livestock breeding. Crop and livestock breeding programmes often rely on elite germplasm, which may not have the necessary genetic diversity that is needed to breed climate-resilient cultivars and breeds (Leigh et al., 2022). To create climate-resilient cultivars and breed types, breeding programmes must consider more genetic variation. Accessing different germplasm, understanding genetic differences and successfully incorporating it into breeding pipelines remains challenging (Atlin et al., 2017; Mrode et al., 2020).

Climate change worsens abiotic stresses (drought, heat and salt) and biotic pressures (pests and diseases). Climate resilience relies on breeding crops with increased tolerance to biotic and abiotic stresses. However, creating comprehensive breeding plans and understanding their relationships remains challenging. Current research is combining phenotyping technologies, molecular markers and genomic tools to identify stress-tolerant genes and characteristics (Prasanna et al., 2022).

Participatory research in crop and livestock breeding is a significant scientific gap, although innovations such as Community Based Breeding Programs (CBBP) (Haile et al., 2023) and the African Dairy Genetic Gain (ADGG) programme (Ojango et al., 2021; Mrode et al., 2022) are already successfully undertaking such an approach in small ruminant and dairy livestock. This involves farmers and stakeholders being actively involved throughout the breeding process, such as issue identification, variety selection and assessment. It aligns scientists' breeding efforts with farmers' needs and goals, increasing the acceptance and impact of new types. However, widespread implementation of participatory breeding remains a barrier due to factors like limited finances, insufficient institutional support and lack of training in participatory approaches among breeders and researchers.

5.8 Conclusions

Climate change has significant negative effects on agricultural productivity through increases in GHG emissions which reduce on-farm productivity by over 30% when climate-resilient varieties and agronomic practices are not used, especially in tropical environments in the Global South. There is a need to breed varieties that can adapt to agricultural practices that contribute to capturing and reducing the excess GHGs generated by agriculture and other industries. Improved agronomic practices, alongside development of new crop varieties that are climate-resilient, could contribute to significant yield improvements in a climate crisis. Climate-smart breeding practices are crucial for addressing climate change concerns and increasing agricultural productivity. However, major gaps and obstacles remain in crop- and livestock-breeding research. Inadequate attention being paid to orphan or under-utilised crops hinders agricultural biodiversity and sustainable agriculture. Participatory research and breeding practices are often under-utilised, making it difficult to incorporate farmer knowledge and preferences into breeding programmes. Scientific impediments include a lack of genetic variation, difficulty relating genotype to phenotype, and dependable bioinformatics tools and analytical pipelines. A lack of adequate finances for R&D also impedes the broad adoption of breeding programmes and resource mobilisation. Improving international collaboration, increasing R&D efforts, mobilising finance, establishing clear metrics and indicators and promoting participatory research and breeding practices are critical recommendations for advancing crop and livestock breeding in a climate context. Policymakers can help develop and adopt climate-resilient crop and livestock varieties, ensuring food security, farmer livelihoods and sustainable agricultural practices in the face of climate change.

Improving climate-smart livestock practices reduces methane emissions and improves farmers' incomes
Hacienda San Jose / ILRI

6

Reduced methane emissions from livestock

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KEY HIGHLIGHTS

- Two clusters of strategies and technologies for reducing methane (CH_4) emissions from livestock are reducing enteric CH_4 emitted from the animal itself, and reducing CH_4 from manure.
- Many technologies on the market, such as CH_4 inhibitors or increasing feed concentrates, are limited to those production systems where there is feed provision, i.e., in zero-grazing and grazing with feed supplementation systems.
- In grazing systems with little to no feed supplementation, the strategies and technologies for reducing CH_4 emissions are much more limited. Here, strengthening climate-smart livestock practices is likely to be the most cost-effective solution for reducing emissions.
- CH_4 emissions from manure can be reduced by improving collection, storage or processing through use of technologies such as anaerobic digesters.
- Reducing CH_4 emissions from livestock should be firmly placed in a broader pathway of a just transition to a more sustainable and efficient livestock sector that supports dependent communities, with high animal welfare concerns and accompanied by reduced consumption of livestock products, particularly where meat consumption is above recommended levels.

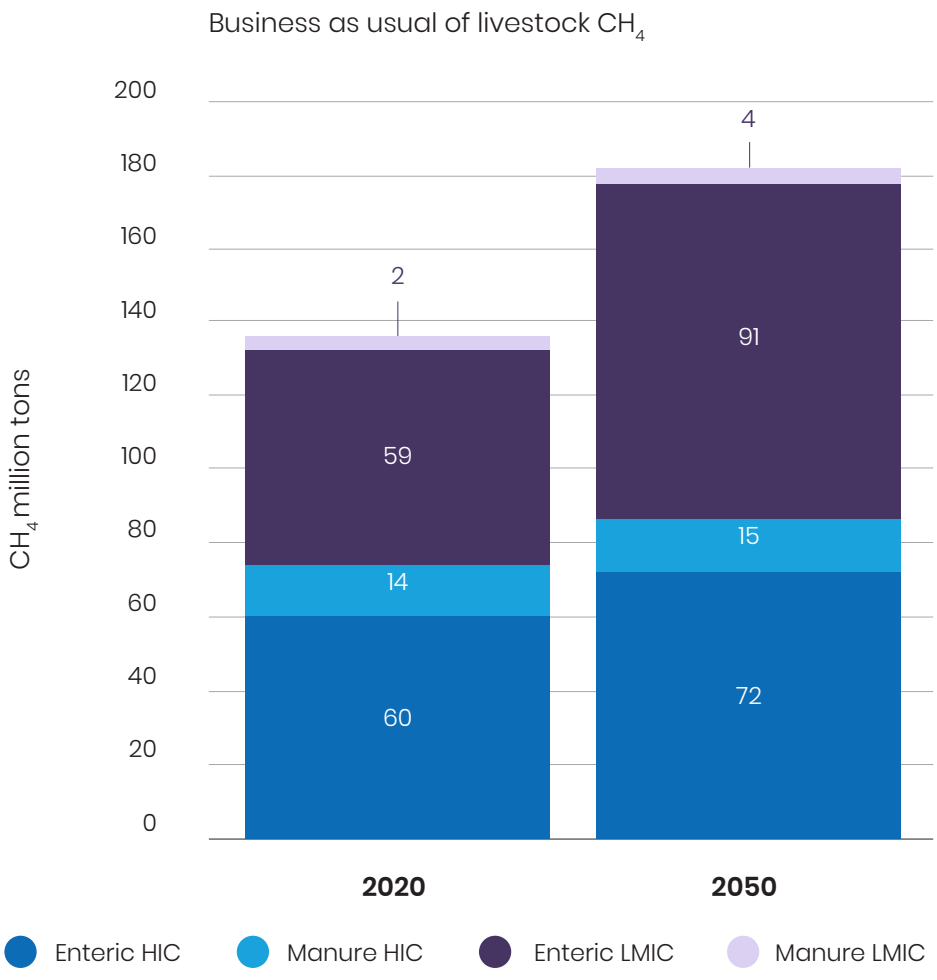
6.1 The context

Livestock contribute 40% of the global value of agricultural outputs in developed countries and 20% in developing ones, supporting the livelihoods and food and nutrition security of almost 1.3 billion people (FAO, 2023a). Livestock-related methane (CH_4) accounts for 30% of global anthropogenic CH_4 emissions (Jackson et al., 2020). About 88% of these emissions comes from enteric fermentation in the digestive tracts of ruminant animals (cattle, sheep and goats), released through belching. The remainder (12%) comes from manure (FAO, 2022c). In more intensive production systems like Californian dairy farms, manure can contribute more CH_4 emissions than enteric fermentation – as much as 55% (Lee, H. & Sumner, 2018).

In 2020, global livestock CH_4 emissions were 136 million tonnes. High-income countries (HICs) and low- to middle-income countries (LMICs) each accounted for around 50% of global livestock emissions, even though per capita consumption of animal-sourced proteins derived from livestock is much higher than the global average in HICs (see Section 3.1). Emissions from HICs are expected to stabilise, while those from LMICs are projected to increase due to a rising demand for animal-source foods as population and incomes increase, reaching 66% of global livestock emissions by 2050 (FAO, 2022c) (see also Figure 6.1). Addressing CH_4 from both enteric fermentation and manure is therefore crucial and is a key component of a transition to more sustainable livestock production.

FIGURE 6.1

Enteric and manure CH_4 emission by HMIC and LMIC for 2020 and projections to 2050



Source: FAO, 2022c

6.2 Strategies and technologies for reducing methane emissions from livestock

There are two clusters of strategies and technologies for reducing CH_4 emissions from livestock. One is to reduce enteric CH_4 emitted from the animal itself, and the other is to reduce CH_4 from manure. Strategies and technologies for reducing animal enteric CH_4 differ from one livestock production system to another (Figure 6.2 and Table 6.3). Many of the technologies currently available for reducing enteric CH_4 are limited to those production systems where there is feed provision, i.e., in zero-grazing and grazing with feed supplementation systems. In grazing systems with little to no supplementation, the strategies and technologies for reducing CH_4 emissions are much more limited.

There are two types of mitigation strategies to reduce enteric CH_4 emissions: (1) absolute mitigation strategies that reduce total CH_4 emissions without affecting animal productivity; and (2) product-based strategies that reduce emissions intensity (CH_4 per unit of product) while increasing animal productivity. Product-based mitigation strategies can reduce absolute CH_4 emissions if increased animal productivity leads to a decrease in animal numbers (Capper et al., 2009), but these may also lead to rebound in situations where the demand for animal-sourced protein is still growing. Strategies and technologies for reducing CH_4 from livestock and manure management systems are summarised in Figures 6.2 and 6.3, with their mitigation potentials and trade-offs provided in Tables 6.3 and 6.4 respectively. Promoting the adoption of multiple strategies tailored to specific livestock production and manure management systems is important as no single strategy is likely to meet reduction commitments. Studies have shown that the effects of mitigation strategies on CH_4 emission reduction can be additive when multiple strategies are deployed simultaneously (Williams et al., 2020; Zhang et al., 2021; Gruninger et al., 2022; Guyader et al., 2015).

FIGURE 6.2

Strategies for reducing enteric CH_4 emissions by effectiveness and applicability across production systems

Zero-grazing production systems	Grazing with feed supplementation	Grazing without feed supplementation
Chemical inhibitors*	Chemical inhibitors*	Tanniferous forages*
Tanniferous forages*	Tanniferous forages*	Pasture and pasture management
Electron sinks*	Electron sinks*	Herd management*
Lipids*	Lipids*	Low-CH_4 emitting animals*
Concentrate	Concentrate	
Feed, forage & forage management	Feed, forage & forage management	
Herd management*	Pasture and pasture management	
Low-CH_4 emitting animals*	Herd management*	
	Low-CH_4 emitting animals*	

Source: Authors
Notes:* Mitigation Srategies that reduce absolute emissions without increasing productivity are marked with an asterisk.

FIGURE 6.3

Manure management strategies and technologies for reducing CH_4 emissions

Manure in wet form/slurry	Manure in solid form	Grazing system[2]
Anaerobic digestion*	Anaerobic digestion*[1]	Short-rotation pasture management
Impermeable covers	Daily cleaning, collection and land spread*	Short-rotation corrals/bomas
Daily cleaning, collection and land spread*	Decreasing storage time*	
Decreasing storage time*	Composting (aeration) with biochar	
Acidification*		
Biofilter		
Solid-liquid separation and/or composting		
Complete removal of manure residues between storage periods		

Source: Authors

Notes:* These mitigation strategies lead to a reduction in CH_4 emissions, as well as reductions in N_2O and NH_3 emissions (Mohankumar Sajeev et al., 2018), whereas other strategies may involve trade-offs.

[1] Anaerobic digestion of manure stored in solid form can count as a CH_4 emission reduction strategy when the captured CH_4 is utilised as a substitute for fossil fuels.

[2] Although the reduction in manure CH_4 emissions achieved through short-rotation corrals/bomas and pasture management may be minimal, these strategies play a significant role in reducing soil carbon loss and N_2O emissions.

6.2.1 Mitigation strategies for enteric CH_4 emissions

This section discusses strategies for mitigating enteric CH_4 from ruminant livestock. The cost-effectiveness and trade-offs of the proposed strategies need to be evaluated by production system and location, using tools such as marginal abatement cost curves and lifecycle assessments.

CH_4 inhibitors can reduce absolute CH_4 emissions by an average of 35% and per unit of product by 32% (Arndt et al., 2022). The most promising CH_4 inhibitor is 3-nitrooxypropanol (3-NOP), which targets a specific enzyme involved in CH_4 production by rumen microbes. Lifecycle assessments over eight years or so have confirmed the sustained inhibitory effect of 3-NOP on CH_4 production (Vyas et al., 2018; Alemu et al., 2021), which can be modified by the nutrient composition of the diet (Kebreab et al., 2023). However, some studies have observed a slight decline in effectiveness over time (Hristov et al., 2023) and a reduced effectiveness of 3-NOP in high-fibre diets (Hristov et al., 2023; Schilde et al., 2021). The cost of 3-NOP can be restrictive and limits its use to more high-value intensive beef production.

Tanniferous forages containing secondary compounds such as tannins, saponins and flavonoids can inhibit CH_4 production when integrated into the diets of grazing animals or when supplemented as forage (Arndt et al., 2022; Ku-Vera et al., 2020). Incorporating tanniferous forages in ruminant diets can decrease absolute CH_4 by 7–16% and CH_4 per unit of milk by 8–26% (Arndt et al., 2022). However, they have the potential to impact the palatability of feed and reduce protein digestion, leading to reductions in productivity. The effectiveness of tannin sources varies and will need to be carefully evaluated before implementation (Arndt et al., 2022; Beauchemin et al., 2022; Ku-Vera et al., 2020).

Alternative electron sinks, particularly through nitrate supplementation, can reduce absolute CH_4 emissions by approximately 17% and product-based emissions by 12–13% (Arndt et al., 2022). However, careful management is required due to the risk of acute toxicity and increased nitrogen excretion if nitrate does not replace another nitrogen source in the diet (Farra & Satter, 1971).

Lipid diet supplementation can reduce absolute CH_4 emissions by 19% and product-based emissions by 12–22% (Arndt et al., 2022) by inhibiting methanogenesis and promoting propionate production. Lipids have a higher energy concentration compared with the feeds they replace, helping maintain animal productivity despite potential reductions in feed intake and fibre digestibility. Careful management is necessary to avoid negative impacts on rumen fermentation and animal health (Schauff & Clark, 1992; Palmquist & Jenkins, 2017). Combining lipid supplementation with other technologies, such as 3-NOP or electron sinks, has shown additive effects in reducing CH_4 emissions (Gruninger et al., 2022; Zhang et al., 2021; Guyader et al., 2015).

Manure anaerobic biodigester for large-scale breaking down of manure to produce biogas and fertilizer at AgroVet-Strickhof, Lindau Zurich, Switzerland.
Mutian Niu / ETH Zurich

Increased inclusion of concentrate feeds in diets can decrease CH_4 emissions intensity by approximately 9%, with a range of 3–15% (Arndt et al., 2022). Additionally, the inclusion of concentrate increased feed intake by around 9%, and improved weight gain (21%) and milk yield (17%) without increasing absolute CH_4 emissions or compromising fibre digestibility (Arndt et al., 2022). However, animal health may be affected when high concentrate levels are fed, and this requires monitoring (Abdela, 2016). Different grains and processing methods have varying effects on CH_4 production, and their composition and processing should be considered (Beauchemin et al., 2022; Arndt et al., 2022). It should also be noted that grains can ferment differently in the rumen depending on their type, and thus different feeding strategies may apply. Often in LMICs concentrate feeds are too expensive for livestock keepers to purchase. For animal welfare reasons it is recommended to vary the concentrate feed proportion in ruminant diets according to the actual energy requirement and not as a tool to mitigate CH_4 emissions.

Genetic selection of low CH_4-producing animals through identification of genetic markers offers a long-term solution for reducing CH_4 emissions in ruminant livestock without compromising productivity (Pickering et al., 2015; Bell et al., 2011). Genetic factors account for around 30% of the variation in CH_4 production among animals (Herd et al., 2014). Balancing CH_4 reduction with other desirable traits is crucial in the selection process. However, there is uncertainty around the heritability of low CH_4, and work is ongoing to better understand this (Pinares-Patiño et al., 2013). More information on animal breeding is provided in Section 5.0.

Climate-smart livestock practices offer a triple win by not only reducing CH_4 emissions but in most cases also increasing productivity and enhancing climate change adaptation and resilience to drought and other climate-related stresses. A combination of practices is likely to have greater returns (Duffy et al., 2021). Commonly low-cost interventions, they should be first in line as intervention investments.

Examples include improved feed, forage and forage management as well as pasture, grassland and grazing management, which can decrease product-based and absolute CH_4 emissions, enhance animal performance and productivity, and increase the adaptation of livestock production systems to climate change. Improved forage and forage management leads to improved forage digestibility by harvesting forages at a vegetative stage (Vargas et al., 2022), while forage preservation with the making of silage or hay can maintain animal productivity during seasons with low forage availability. Supplementing livestock diets with perennial legumes and high-starch forages such as corn silage and small-grain cereals in livestock diets can increase animal productivity. Crop residues are an important animal feed supplement in more extensive livestock systems in LMICs during times when other feed sources are limited.

More effective pasture, grassland and grazing management practices such as participatory rangeland management and silvopastoralism (FAO, 2022b) are also promising. Pre-grazing and post-grazing sward height and biomass considerations can lower CH_4 intensity (Hristov et al., 2013a), decrease emissions and improve opportunities for carbon sequestration, though in some cases N_2O emissions from manure and fertiliser may increase (FARM, 2017). As part of feed management, adjusting the nutrient content and digestibility of the feed can help optimise diet composition and improve feed efficiency, optimise resource use and reduce product-based emissions.

Other examples focus on the management of the herd and its health. Herd management through removing unproductive animals and maintaining optimal age structure can reduce product-based as well as absolute CH_4. Improved feeding management such as optimisation of diet nutrient composition to the production state of an animal (phase feeding) can be an option. Selective breeding can develop breeds with enhanced productivity and environmental adaptability. Improving animal health and welfare can indirectly reduce product-based CH_4 by improving digestion, nutrient utilisation and animal performance, and can direct feed energy towards production rather than immune defence or reacting to stress.

6.2.2 Manure management strategies and technologies for reducing CH_4 emissions

Approaches cover all stages of manure management, including its accumulation in animal houses, collection, storage, processing and application. However, it should be noted that there are often trade-offs, with a reduction in CH_4 resulting in an increase in other GHG emissions. A meta-analysis conducted by Mohankumar Sajeev et al. (2018) of 89 peer-reviewed studies showed that only three

out of the eight abatement options considered (frequent removal of manure through regular cleaning and decreased storage time, anaerobic digesters and manure acidification) simultaneously reduced ammonia, nitrous oxide and methane emissions. In all other cases, trade-offs were identified.

Improving manure collection and storage: Often, simple interventions can reduce CH_4 emissions from manure by managing moisture and reducing anaerobic conditions (Gerber et al., 2013; Hristov et al., 2013b; FARM, 2017). Options include improving covers for stored manure, particularly impermeable covers like anaerobic digesters for capturing and utilising CH_4 from liquid manure (Kupper et al., 2020); storage treatments that provide mechanical or intermittent aeration (Amon et al., 2006); decreasing manure storage time, particularly in warmer climates; and regular cleaning of liquid manure from livestock housing and storage tanks and its storage outside housing in cold temperatures (Jayasundara et al., 2016; Ulens et al., 2014).

Using straw or sawdust as bedding can reduce CH_4 emissions by 23% in liquid manure storage systems. However, N_2O increases through nitrification and denitrification processes in the solid manure (Wang et al., 2017). Manure can be spread on the land though timing is important to prevent run-off and pollution of water sources. Incorporation through a sub-surface soil injection can also be effective, particularly when paired with anaerobic digestion and solids separation, as this improves infiltration – see, for example, its application in flooded rice fields (Montes et al., 2013). Solid liquid separation can be another technology, separating dry matter from liquid manure using, for example, a screw press or centrifuge; this optimises manure handling and storage, improving nutrient management and reduction of CH_4 emissions by 41% (Amon et al., 2006; El Mashad et al., 2023). Manure drying reduces the liquid content of manure for easier storage and transport, particularly when used in poultry operations. However, manure drying may increase N_2O emissions (EPA, 2022).

Composting of bedding or other manure-related solids reduces CH_4 emissions from manure but may increase N_2O and NH_3 emissions (El Mashad et al., 2023). It also improves soil biodiversity and water retention capacity, maintaining soil organic carbon. Composting requires careful management (FARM, 2017) and the use of additives can make composting more efficient. A global meta-analysis by Cao et al. (2019) showed that the use of additives such as biochar in compost resulted in significant reductions in CH_4 (68.5% on average) and other GHG emissions measured as global warming potential. Biofilters are widely utilised to reduce CH_4 and NH_3 emissions from the extracted air of animal houses and stored manure (Gerber et al., 2013; Janni et al., 2014; Akdeniz & Janni, 2012), and from composting (Zhou, 2017), though this may lead to an increase in N_2O emissions of 12–81% (Akdeniz & Janni, 2012; Janni et al., 2014).

Pasture-based management is a system of raising animals on fenced pastures, rotating them between grazing areas to improve pasture health and evenly spread manure. This approach, particularly suitable for ruminants, can significantly reduce CH_4 emissions from manure management, especially when transitioning from solid storage or anaerobic lagoon systems. Challenges include the need for suitable land, weather-related issues, and the costs of fencing and maintenance. However, this method also promotes natural nutrient return and carbon sequestration in the soil (FARM, 2017).

Another technology is **manure acidification**, where the addition of acids like sulphuric acid reduces CH_4 during storage by up to 96%, as well as NH_3 emissions (Petersen et al., 2012; Habtewold et al., 2018; Petersen et al., 2014; Ma et al., 2022). Acidified manure typically does not affect crop production negatively as its pH is near neutral. However, further research is required to understand its long-term impact on soil pH and overall health.

Anaerobic digesters or biogas digesters utilise micro-organisms to break down organic materials like manure in an oxygen-devoid environment, generating biogas (CH_4 and CO^2) and nutrient-rich fertiliser (digestate). Capturing biogas and burning it for energy directly reduces CH_4 emissions and can replace fossil fuel consumption. Utilising digestate as a fertiliser enhances the mitigation effect by replacing fertilisers derived from fossil fuels. The addition of biochar in anaerobic digesters has been shown to increase CH_4 recovery by 32% (Manga et al., 2023). In the case of liquid manure storage, anaerobic digesters can capture around 50–70% of CH_4 depending on climate and can result in a CH_4 reduction of over 90% when the captured CH_4 is utilised as a substitute for fossil fuels (Steinfeld et al., 2006). Options are available for operations at different scales: micro-scale anaerobic digesters, common in households in Africa, South America and Asia (IEA, 2017; Clemens et al., 2018; SNV, 2022); industrial-scale digesters with around 132,000 installations globally, producing heat and electricity (Scarlat et al., 2018); and large-scale digesters with biogas upgrading to biomethane, found in approximately 700 facilities worldwide. If all collectible manure were to be utilised, anaerobic digestion technology could produce 10 billion tonnes of nutrient-rich fertiliser and capture enough CH_4 to generate 2,600–3,800 terawatt hours of energy (WBA, 2019). This is enough to provide electricity for 330–490 million people or meet 100% of the energy needs of global agriculture, as well as to offset 930–1260 MT CO^2 emissions per year of GHG emissions or 13–18% of current livestock-related emissions (WBA, 2019).

CASE STUDY 6.1

Methane reduction with feed additive in dairy production systems in a HIC

Bovaer® is a feed additive that contains the compound 3-NOP, a methane-reducing compound, and is being piloted in 158 dairy farms in the Netherlands. The pilot project successfully integrated Bovaer® into the regular farming activities of these farms without compromising animal health or milk production. Results showed a significant (28%) reduction in enteric CH_4 emissions, equivalent to 20,000 MT CO^2e per year from 20,000 animals. The mitigation effect is calculated using the simplified methane reduction formula (3-NOP dose) from the meta-analysis on use of Bovaer® in dairy cows from Kebreab et al., 2022. For each dairy farm, information was collected for the six-month pilot period by FrieslandCampina, where Agrifirm provided the ration and Bovaer® dose information for each of the farms. During the trial period, milk production, milk quality, animal health and welfare were monitored by the farmers and feedback was collected by FrieslandCampina and Agrifirm. Participating farmers expressed positive feedback, emphasising the ease of incorporating Bovaer® into their feed regime, and reported no impact on milk production, milk composition, animal health or animal behaviour. However, as there is no direct benefit to farmers, the cost associated with the supplementation of Bovaer® will need to be met through tools such as subsidies, carbon markets, cost sharing with value chain actors, or passing the costs to end users.

Source: personal communication, Rjinders (2023) and *https://www.dsm.com/corporate/news/news-archive/2023/bovaer-is-ready-for-roll-out-in-the-netherlands.html*

CASE STUDY 6.2

Reduction of product-based enteric methane emissions in a LIC

This case study in Kenya assessed the implementation of Climate Smart Agriculture (CSA) practices in three dairy production systems, namely, no graze, semi-intensive and extensive systems. Depending on the livestock system, CSA practices employed included feed processing, fodder improvement, feed preservation and supplements, animal health interventions, improvement of pastures, feeding of by-products, water harvesting and stall-feeding, among others. The results showed that implementing common CSA practices led to enhanced milk yields (by 34%) and reduced GHG emissions per unit of milk (by up to 20%) across dairy production systems. Effects were most pronounced in extensive production systems. However, upfront investment costs were important barriers to the use of these practices. Moreover, the results demonstrated the importance of the establishment of policy and financing mechanisms to decrease the perceived risks involved in investing in CSA practices.

Source: Caulfield et al. (2023)

CASE STUDY 6.3

CH_4 mitigation in a LIC: biogas digesters in East Africa

The Africa Biogas Partnership Programme (ABPP), active from 2009–2020, was a joint initiative funded by the Dutch government, managed by Hivos, and supported by SNV, EnDev and the governments of Burkina Faso and Ethiopia. Spanning five countries (Burkina Faso, Ethiopia, Kenya, Tanzania and Uganda), the ABPP aimed to develop market-oriented biodigester businesses (Clemens et al., 2018). By 2019, it had installed 73,000 biodigesters, providing sustainable energy and biofertiliser to around 325,000 people, primarily women and children (SNV, 2021). The programme also boosted awareness of sustainable technology, nurtured emerging companies, reduced indoor air pollution, and helped enhance agricultural productivity. The project was able to develop a carbon finance mechanism making use of the Clean Development Mechanism and Gold Standard certification schemes. For example, 18,346 biodigesters installed in Kenya saved 260,600 tons of wood. A total of 20,852 households used the digestate as fertiliser, and it increased crop productivity on average by 25% and cut CO^2e emissions by 378,732 tonnes, with earnings of USD 4 million from the carbon market (*Gold Standard Marketplace*).
Source: *http://www.africabiogas.org*

6.3 Metrics for measuring progress

There are no universal goals (metrics) on emissions reductions from the livestock sector, but there are targets set by international coalitions. For example, the Global Methane Pledge currently has 111 participating countries committed to cutting anthropogenic CH_4 emissions by at least 30% by 2030, with similar targets from the Global Roundtable for Sustainable Beef and the Net Zero Dairy Initiative. The European Roundtable for Sustainable Beef has a more imminent target of reducing GHG emissions by 15% by 2025. Additionally, the Forest, Land and Agriculture (FLAG) tool of the Science Based Target initiative and the Accountability Framework provide a standard method and livestock emission monitoring tools for the commercial sector.

Many countries have developed targets within livestock sectors as part of Nationally Determined Contributions (NDCs), with reductions ranging from 3–30% by 2030 from different starting points. A review of 164 countries found that 54 (36%) included livestock mitigation measures in their NDCs, and 39% (64) included livestock adaptation measures. Mitigation priorities included manure management (20% of 164 countries), feed management (16%) and silvopastoralism (16%). Among the top 10 countries with the highest mitigation potential for enteric fermentation and manure management, seven had livestock mitigation measures. Only 12 countries included specific GHG targets for livestock (Belize, Burundi, Côte d'Ivoire, Cuba, Guatemala, Kyrgyzstan, Liberia, Mongolia, New Zealand, Serbia, South Sudan and Uganda). Where specified, emission reductions ranged from 3% to 40%. Thirty countries have relevant livestock mitigation measures aligned with the Global Methane Pledge of reducing CH_4 by 30% by 2030 (Rose et al., 2022).

6.4 Actors and change agents in the livestock landscape

Table 6.1 table provides examples of various change agents who can push and implement the agenda on reducing CH_4 emissions from the livestock sector. The AIM4C has also launched two sprints, namely the Enteric Fermentation R+D Accelerator (led by the Global Methane Hub) and Livestock, Climate and System Resilience (led by several CGIAR Centers). Such international collaborations for knowledge and expertise sharing are important for accelerating efforts towards emissions reductions in the sector.

TABLE 6.1 **Actors and change agents in reducing methane emissions from livestock**

Role	Reducing methane emissions from livestock
Long-term vision and action plan	**International:** Global Methane Pledge, Climate & Clean Air Coalition, GRA, International Renewable Energy Agency (IRENA), Clean Cooking Alliance (CCA), ENERGIA (International Network on Gender and Sustainable Energy), Dairy Net-Zero Initiative, Sustainable Agriculture Initiative, Leaders Pledge for Nature, World Farmers Organisation, Sustainable Fibre Alliance, Just Rural Transition (JRT) initiative and JRT Policy Action Coalition **Regional:** regional economic communities, European Union, African Union **National:** relevant ministries (agriculture, livestock and fisheries, environment and climate change, energy, health, women and children)
Demand creation and management	**International:** FAO, UNEP, UNDP, UN Economic Commission for Africa, IFAD, World Bank, Global Dairy Platform, Greenhouse Gas Emissions Monitoring, Global Methane Hub, Global Methane Initiative, IRENA, CCA, WHO, Hivos, GIZ, SNV, ENERGIA, supermarkets, fashion houses and other livestock product retailers **Intergovernmental political forums:** African Union, G7, G20, Leaders Pledge for Nature **Regional:** regional economic communities, European Union, OECD, CAADP **National:** relevant ministries (agriculture, livestock and fisheries, environment and climate change, energy, health, women and children), livestock producers and consumers **Civil society:** environmental organisations, livestock food system actors **Private sector:** e.g., Danone
Infrastructure and supply chains	**Private sector:** Elanco (animal health/feed), Agrinz Technologies, Air Liquide, DMT International, Shell, Homebiogas Ltd, Anaergia, sistema bio, Renergon (several manure and biogas companies) Livestock value chain actors: e.g., Danone, JBS SA, Tyson Foods, Maple Leaf Foods, Marfrig, Fonterra, Minerva, Cargill, Nestle, livestock producer associations, boards and alliances, supermarkets, fashion houses and other livestock product retailers
Finance and investment	**Global:** Green Climate Fund, International Finance Corporation, Global Environment Facility, European Investment Bank, Erol Foundation **Private sector:** FAIRR Initiative, Good Food Finance Network **Impact investors:** & Green, Bezos Foundation, Bill and Melinda Gates Foundation, development agencies such as IFAD, USAID, World Bank, GEF, AFDB, ADB and other international finance agencies, World Economic Forum **Others:** Environmental Defense Fund (USA), ClimateWorks Foundation, Global Methane Hub,
Research and innovation	CGIAR, particularly ILRI, the Alliance of Bioversity International and CIAT, and ICARDA, FAO, GRA, Greenhouse Gas Emissions Monitoring, Global Methane Initiative (Livestock Research Group), Greener Cattle Initiative, AIM4C, Gilbert Initiative, many universities and laboratories
Market structures	Changing Markets Foundation
Standards and certification	Verra, Gold Standard, Science Based Target initiative (FLAG) and Accountability Framework, Committee on Food Security – Principles for Responsible Food Investment in Agriculture and Food, IFC Performance Standards on Environmental and Social Responsibility
Trade conditions	FAIRR Initiative, Institute for Agriculture and Trade Policy, World Bank and FAO Investing in Sustainable Livestock Guide
Knowledge, capacity and skills	CGIAR Centers, GRA, AGNES, livestock producer associations, boards and alliances
Social engagement and impact	Livestock and farmer organisations (global, national and local), NGOs, CSOs, and relevant research institutes and universities that undertake impact evaluation work
Landscape coordination	Climate & Clean Air Coalition, Agriculture Innovation Mission for Climate (AIM4Climate), Global Alliance for Sustainable Livestock, Global Dairy Platform, Greenhouse Gas Emissions Monitoring, Global Methane Hub, Global Methane Initiative, FAIRR Initiative, Global Roundtable for Sustainable Beef, World Biogas Association

Source: Authors

Notes: ADB = Asian Development Bank; AFDB = African Development Bank; AGNES = African Group of Negotiators Expert Support; CAADP = Comprehensive Africa Agriculture Development Programme; CIAT = International Center for Tropical Agriculture; GEF = Global Environment Facility (UNEP); ICARDA = International Center for Agricultural Research in Dry Areas; OECD = Organisation for Economic Co-operation and Development.

6.5 Barriers to implementation

6.5.1 Lack of government policies, incentives and regulatory standards for technology uptake

There is a lack of supportive government policies – including public financial assistance, subsidies, financial (including tax) incentives and regulatory frameworks – to encourage farmers to take up or continue use of technologies and sustainable livestock practices that improve productivity, reduce livestock numbers and/or reward better outcomes for climate and biodiversity. There is also a need to phase down existing policies, programmes and fiscal support that lock in industrial meat production and consumption (Verkuijl et al., 2022).

For certain technologies, such as feed additives, regulatory standards are mainly missing. Where they exist, they are limited to specific regions, thereby restricting their use in other areas. In addition, regulatory frameworks and policies related to, for example, manure management can vary across jurisdictions, resulting in inconsistent or burdensome regulations and permitting processes, or a lack of financial incentives. There is a need to improve measurement, reporting and verification (MRV) for livestock emissions, particularly by LMIC governments (Wilkes et al., 2017b). In LMICs, many governments do not have appropriate inventory methodologies in place (tier 2) to report on their mitigation efforts. More streamlined and effective MRV for producers could lead to greater carbon market opportunities.

A catlle herd returning to the pasture just outside Zorro village, Burkina Faso.
Ollivier Girard / CIFOR

6.5.2 Cost, financial and market constraints

The review in Section 6.3 shows that most enteric CH_4 mitigation strategies that reduce absolute CH_4 emissions do not offer improvements in animal productivity, leading to additional costs for producers without corresponding revenue gains. Though there are more options to reduce emissions from systems that have feed supplementation and, even more effective, for systems that have zero-grazing, the costs of feed additives or advanced manure management methods can be prohibitive for farmers. There are limited functioning markets providing carbon credits for reduction of emissions from livestock – one exception is carbon offsets for use of biogas digesters. Private sector investment is low, while public sector incentives to bring down the costs are missing. On the other hand, financial resources for upfront investments can constrain the adoption of product-based mitigation strategies,

which have the potential to increase farm productivity and revenues. The right infrastructure and products (e.g., livestock fencing or disease treatments) may not be locally available, particularly in LMICs. Additionally, power asymmetries between stakeholders may result in unjust transactions, forcing change and/or limiting uptake and expansion of technologies and strategies.

Consumer willingness to pay higher prices for animal products with reduced carbon footprints may be limited: a study has shown that health- and environment-related information may not significantly motivate change of diet (Katare et al., 2023). Livestock investors are increasingly assessed for risks associated with climate change and unsustainability – see FAIRR's *livestock producer assessment* index. Governments, particularly in LMICs, require technical assistance in obtaining financing and implementing initiatives, and in reporting their progress in mitigation efforts, especially when critical questions still remain largely unanswered on where and in what to invest (Bonilla-Cedrez et al., 2021).

The amount of climate finance given to the livestock sector is a small proportion of that directed to the agricultural sector more broadly (Bonilla-Cedrez et al., 2021). If a just transition to more sustainable low-emission livestock production systems is to be achieved, then there is a need for more public and private sector climate finance directed to the livestock sector, and for innovative schemes, guarantees and blended finance supported with appropriate regulations.

6.5.3 Many technologies are still in their early stages of development

The technologies listed in Section 6.2 are market-ready and, in most cases, commercially available, yet many remain unprofitable in their application due to added production costs without a corresponding increase in farm productivity or resource efficiency. The reported mitigation potentials for these technologies largely stem from tests conducted under idealised experimental conditions. Therefore, it is essential to further evaluate these potentials in diverse on-farm production systems and conditions.

Potential technology trade-offs on biodiversity and animal welfare also need to be better understood, together with the full impacts of strategies and technologies on livestock health and productivity. In the rush to find quick and easy and cost-effective solutions, technologies may be released without full testing and accompanying standards. The involvement of the private sector is vital, but this should not be at the risk of immature technologies with limited testing appearing on the market. There are gaps in investment, and international collaboration is needed to speed up the development and fuller testing of technologies to reduce livestock emissions and manage manure, standardise where appropriate, and identify optimal clustering of technologies for both environmental and production gains, together with animal welfare (Reisinger et al., 2021), while ensuring multi-stakeholder access to these technologies.

6.5.4 Technical complexity, limited awareness and capacity

Some manure mitigation strategies, such as anaerobic digestion systems or advanced manure management technologies, may require specialised technical knowledge for proper implementation and operation. In addition, there is limited awareness and knowledge of available technologies to reduce CH_4 emissions (and of their co-benefits) among stakeholders. Farmers may require technical assistance, training and capacity building to implement CH_4 mitigation technologies and strategies effectively (CCAFS, 2019). Social and cultural norms can influence the acceptance and adoption (or not) of new practices. Resistance to change or scepticism about the effectiveness of mitigation strategies can impede their widespread implementation (Katare et al., 2023). Livestock farmers are often physically dispersed across large areas, making outreach and the provision of national livestock extension services costly and often limited.

6.6 Recommendations for reducing methane emissions from livestock

6.6.1 Foster international collaborations for RD&D through knowledge exchanges

We recommend international knowledge sharing collaborations to exchange best practices, research findings, and innovative technical and policy solutions for mitigating CH_4 emissions from livestock systems. This includes organising training programmes, knowledge sharing via digital resources and platforms, large-scale collaborative research initiatives (e.g., on next-generation technologies and technologies in early phases, such as vaccines, low-emission breeds, and efficient and affordable anaerobic digesters), learning exchanges for researchers and technicians, and agreements on common data sharing protocols. Organisations and existing partnerships like the GRA, CGIAR, FAO, Global Methane Hub, Global Methane Pledge, Climate and Clean Air Coalition and Net Zero Dairy Initiative, with the support of donors, national ministries, major beef and dairy suppliers (e.g., JBS, Marfrig, Minerva, Danone, FrieslandCampina, Nestle and Fonterra) and private sector input suppliers can form multi-stakeholder platforms for the purpose of knowledge sharing across multiple partners. Global platforms such as AIM4C can play a role in fostering global research collaboration and investment, as they already do through innovation sprints. Research institutions such as the International Institute for Applied Systems Analysis, Postsdam Institute for Climate Impact Research, and PBL Netherlands Environment Assessment Agency integrate new technical options into modelling to support national climate strategies and NDCs.

6.6.2 Support knowledge sharing for policies for standards and regulations and encourage the private sector to promote scale-ready technologies

Countries, particularly the signatories of the Agriculture Breakthrough Agenda, should use existing mechanisms such as PD to share information on existing policies, standards and regulations and assess their relative effectiveness in reducing CH_4 emissions from livestock, improving and harmonising. The same mechanisms can be used to encourage private sector adoption of ready-to-scale CH_4-reducing technologies and mitigation practices by sharing international experiences of innovative policies, innovative financial instruments and business models (e.g., eco-subsidies for enteric CH_4 mitigation additives by the Dutch and Belgian governments), and business models in LMICs to invest in the expansion of micro-scale digesters.

In addition, global stakeholders including the G7, G20, African Union, OECD, donors and funders, partnerships and platforms (e.g., the Netherlands Food Partnership) and science partners (e.g., the GRA, CGIAR and WRI) should support the development of global and national supportive policies, standards and regulations guiding livestock CH_4 reduction, including regulatory standards for feed additives and manure management in contexts where such technologies and strategies are feasible, the approval processes for which need to be harmonised and streamlined.

More finance from government in terms of subsidies and other financial incentives, and from the private sector in terms of climate finance, needs to be directed to the livestock sector through innovative mechanisms to support a just transition to more sustainable low-emission livestock production systems, particularly in LMICs. Policies, standards and regulations need to provide a supporting framework for addressing the power imbalances that often exist between the different stakeholders involved – in both HICs (Verkuijl et al., 2022) and LMICs. This will help to establish a more level playing field for more participatory planning for change and for necessary negotiating that reaches agreement.

6.6.3 Establish robust, cost-effective and appropriate metrics and MRV systems

Governments, with support from international bodies, need to develop international and national targets and baselines for livestock CH_4 monitoring and establish MRV systems (including tier 3 reporting) to support national reporting of mitigation progress. Science partners including the GRA, Global Methane Hub, CGIAR, FAO, WRI and research institutes need to support the improvement of GHG inventories and validated tools and models to estimate and measure CH_4 emissions and reductions brought about by mitigation strategies and technologies, including from climate-smart livestock practices. More data are required on potential mitigation strategies. There need to be common definitions, shared data sources and data transparency. Some improvements in measurement and reporting are being made by the application of machine learning, improved methods for collection of activity data, innovations in remote sensing to estimate livestock CH_4 emissions at large scales, and transparency in tracking emissions in supply chains. Additionally, there has been some headway in establishing systems to track livestock systems adaptation (Njuguna & Crane, 2023).

There is a need for more cost-effective and streamlined MRV to estimate and report emission reductions, reducing the costs of carbon market participation for livestock producers and others. Carbon project and corporate partners and regulators such as Verra and Gold Standard need to increase the robustness, transparency, consistency and accuracy of carbon and livestock CH_4 emissions quantification.

6.6.4 Invest in capacity building programmes and technical assistance for national and regional partners

There is an urgent need for investments in building the capacity of various stakeholders through technical assistance programmes – at national, regional and global levels – on ways of reducing emissions from the livestock sector while addressing important potential trade-offs in relation to biodiversity loss, nutrition, animal welfare, spread of zoonotic diseases and antimicrobial resistance. The World Bank, IFAD, Green Climate Fund, BMGF, Bezos Earth Fund, USAID, GIZ, FCDO, Climate and Clean Air Coalition, national extension services, cooperatives, GFRAS, Access Agriculture, Digital Green and other technical advisory organisations should support regional climate hubs that provide information on emission reduction technologies in simplified formats, and disseminate best practices though training programmes, researcher and technician exchanges, demonstration farms, workshops and guidelines to build producers' knowledge and skills for implementing CH_4 and mitigation strategies. The GRA, FAO, CGIAR and other global and national science and research institutions should provide technical assistance to national ministries and multilateral banks on programme design and MRV. Table 6.2 sums up these recommendations.

TABLE 6.2 **Recommendations for promoting technologies and measures to reduce methane emissions from livestock**

Summary of Recommendations	Relevant partners for implementation	Recommendation applicable at levels		Themes*
		Domestic	International	
Promote international knowledge sharing collaborations to exchange best practices, research findings, and innovative technical and policy solutions for mitigating CH_4 emissions from livestock systems	GRA, CGIAR, FAO, Global Methane Hub, Global Methane Pledge, CCAC, Net Zero Dairy Initiative, donors, governments, IIASA, PIK, PBL and private sector beef and dairy companies		✓	Theme 4
Support information sharing on existing policies, standards and regulations for better public policymaking, increase climate finance, and encourage the private sector to promote ready-to-scale CH_4-reducing technologies	PD, G7, G20, African Union, OECD, national governments, donors and funders, partnerships and platforms and science partners e.g., GRA, CGIAR, WRI and other global and national science and research institutions	✓	✓	Themes 2 and 5
Develop international and national targets and baselines for livestock CH_4 reductions and establish MRV systems (including tier 3 reporting) to support national reporting	GRA, Global Methane Hub, CGIAR, FAO, and WRI and other research institutes. Carbon project and corporate partners and regulators, e.g., Verra, Gold Standard	✓	✓	Theme 3

Source: Authors

Notes: * Theme 1: Climate finance; Theme 2: Policies, regulations and innovations; Theme 3: Metrics, indicators and standards; Theme 4: Research and development and demonstration (RD&D); Theme 5: Private sector, markets and trade

6.7 Gaps in science knowledge

Technologies and strategies to reduce CH_4 emissions have been described above. However, their effectiveness and applicability in specific farming contexts are still not well defined; this is also the case for the potential biodiversity, animal welfare and other trade-offs. Low-emission pathways for production systems, making use of offsets within livestock systems, and farmer incentives and motivation to change are also knowledge gaps. Further studies are needed to assess the specific on-farm mitigation potential of different strategies in diverse regions and farming systems. Economic analysis can help identify the most cost-effective strategies and guide resource allocation for mitigation efforts.

More research is needed to understand the long-term effects of the technologies discussed in Section 6.2 (which are currently being implemented) on CH_4 reduction (Beauchemin et al., 2022) and on animals (Beauchemin et al., 2022; Arndt et al., 2022). This includes a better understanding of the microbial communities in the rumen and their role in CH_4 production. Research is also needed to explore the interactions between host genetics, diet, animal nutrition and the rumen microbiota to optimise enteric CH_4 mitigation. Interactions between effective mitigation strategies when implemented at the same time need to be studied. Further research is also needed to better understand manure CH_4 production from anaerobic digestion, composting and other treatment methods in different livestock production systems and geographical contexts.

There are also significant gaps in technologies still in development. For example, macroalgae (seaweed) has gained global attention as when fed to cattle under experimental conditions it has resulted in significant reductions in enteric CH_4 (Roque et al., 2019). However, there are still gaps in understanding its potential and long-term effects on animal and human health due to its active compound bromoform, which is cancerogenic, as well as the seaweed's high heavy metal content (Roque et al., 2019; Machado et al., 2014; Moate et al., 2021; Higgins et al., 2019; Wijffels et al., 2013). Other developing technologies include the cow mask (a methane oxidising device), feed additives delivery technology, direct emissions capture from barn-fed animals, immunisation against methanogens, and the creation of genetically modified grasses or legumes with anti-methanogenic properties.

Additionally, improving the accuracy, efficiency and cost-effectiveness of CH_4 measurement and monitoring techniques is essential for assessing the efficacy of mitigation strategies. More research is needed to develop innovative and reliable methods for measuring CH_4 emissions from individual animals, as well as scalable approaches for monitoring emissions at the herd and national levels. This will help to improve national emission inventories while demonstrating the workability of emission reduction measures. Comprehensive lifecycle assessments are needed to evaluate the environmental impact and trade-offs of different mitigation strategies. A more comprehensive approach to tracking CH_4 and developing accurate emission estimates encompassing both animals and manure management is needed.

6.8 Conclusions

The technologies and strategies described here have significant potential for reducing livestock CH_4 emissions. However, the effectiveness and feasibility of these strategies vary depending on the specific livestock production system, regional context, biodiversity, animal welfare and other potential trade-offs and economic considerations (Tables 6.3 and 6.4), and more research is required to fully understand these. Measures which have positive outcomes on several fronts (e.g., a technology that reduces emissions while also increasing productivity, safeguarding natural resources and building resilience) should be prioritised, while keeping in mind the context specificity of particular production systems and the overall socioeconomic contexts of the relevant HICs and LMICs.

TABLE 6.3 **Summary of mitigation strategies for enteric CH_4 emissions**

Technological innovations	Sustainably increases agricultural productivity and incomes[1]	Reduces absolute CH_4 emissions[2]	Reduces CH_4 emission per product2	Safeguards soil, water resources and natural ecosystems[3]	Adapts and builds resilience to climate change[4]
Chemical inhibitors	0 to ↑	↓↓↓	↓↓↓	↑ (UPS)	0
Tanniferous forages	0 to ↑	↓	↓	↑/↓ (UPS, MAN)	↑
Electron sinks	0 to ↑	↓	↓	0 to ↓↓↓ (UPS, ANI, MAN)	0
Lipids	0 to ↑	↓↓	↓ to ↓↓	↑↑↑ (UPS, MAN)	0
Concentrate intake	↑↑	↑	↓↓	↑↑↑ (UPS, MAN)	↑
Genetic selection of low producing CH_4 animals	↑ /↓	↓	?	?	↑ to ↑↑↑
CSA practices	↑ to ↑↑↑	↑ /↓	↓to ↓↓↓	↑↑ (UPS, MAN)	↑ to ↑↑↑
Forage and forage management	↑ to ↑↑	↑	↓	↑ /↓ MAN)	↑ to ↑↑
Pasture and grazing management	↑ to ↑↑	↑	↓	↑ /↓ MAN)	↑ to ↑↑
Herd management	↑ to ↑↑	↑ /↓	↓ to ↓↓↓		↑ to ↑↑↑
Feeding management	↑ to ↑↑↑	↑ /↓	↓ to ↓↓	↑ /↓ MAN)	↑ to ↑↑↑
Animal health care	↑ to ↑↑	↑ /↓	↓ to ↓↓	↑ /↓ MAN)	↑ to ↑↑↑
Selective breeding	↑	↑ /↓	↓	↑ /↓ MAN)	↑ to ↑↑↑

Source: Authors

Notes: 1↑ = small increases; ↑↑ = medium increases; ↑↑↑ = large increases; 0 = minimal or no change; ↑/↓ = variable results

2↓ = small decreases (≤15%); ↓↓ = medium decreases (15–24%); ↓↓ = large decreases (≥25%); ↑ = increases? = more research

3↑/↓ = increases in some emissions and decreases in others; ↑ = small increases; ↑↑ = medium increases; ↑↑ = large increases; ANI = increases in emissions of enteric N_2O; MAN = increases in emissions of manure CH_4 and N_2O; UPS = increases in upstream emissions of CO^2 from fossil fuel use or N_2O from fertiliser applications

4↑ = small adaptation and building resilience to climate change; ↑↑ = medium adaptation and building resilience to climate change; ↑↑↑ = large adaptation and building resilience to climate change; 0 = minimal or no change in adaptation and building resilience to climate change

TABLE 6.4 **Summary of mitigation strategies for manure CH_4 emissions**

Technological innovations*	Sustainably increases agricultural productivity and incomes[1#]	Reduces CH_4 emissions[2]	Estimated manure CH_4 emissions in domain of relevance ($MT\ CO^2e$)[3]	Safeguards soil, water resources and natural ecosystems #	Adapts and builds resilience to climate change #
Solid storage	Low to medium	High	232	Low to medium	Low to medium
Decreasing manure storage time	Medium	High	275	Medium to high	Medium to high
Aeration	Low	Medium to high	102	Low to medium	Low
Solid–liquid separation	Medium	High	245	Medium to high	Medium to high
Anaerobic digesters	Medium	Very high	275	Medium to high	Medium to high
Composting	Medium to high	High	275	Medium to high	Medium to high
Daily spread	Medium to high	High	232	Medium to high	Medium to high
Pasture-based management	Medium to high	Variable		Medium to high	Medium to high
Manure drying	Low	High	232	Low to medium	Low to medium
Semi-permeable covers and natural or induced crusts	Low to medium	High	232	Medium to high	Low to medium
Manure acidification	Medium to high	Very high	165	Medium to high	Medium to high
Manure incorporation in soil and time of application	Medium to high	Low	Not calculated (marginal)	Medium to high	Medium to high
Biofilters	Low	Low to medium	Not calculated	Low to medium	Low

Source: Authors

Notes:

[1]Agricultural productivity is achieved when manure is utilised for crop and forage production as biofertiliser

[2]Low = ≤10% mitigating effect; medium = 10–30% mitigating effect; High = ≥30% mitigating effect; Very high = ≥60% mitigating effect. Mitigating effects refer to percentage change over a standard practice. For a detailed discussion see Hristov et al. (2013b) and Gerber et al. (2013).

[3]Estimates based on FAO (2013a); FAO (2013b); and Gerber et al. (2013)

* Co-benefits and trade-offs of the technologies for emissions of other gases and nutrient quality of the final manure product include: manure stored (↑ N_2O), decreasing storage time (↑ N_2O), aeration (↑ CO^2 for forced aeration from energy usage and ↓ manure nitrogen), anaerobic digesters (↑ plant-available nitrogen, ↓ odour, ↓ pathogen, ↓ N_2O from digestate application), composting (easy to transport, ↓ plant-available nitrogen, ↓ odour, ↓ pathogen, ↑ N_2O, ↑ NH_3), daily spread (↑ N_2O), pasture-based management (↑ N_2O), drying (↑ N_2O), semi-permeable covers and natural or induced crusts (↓ odour, semi-permeable cover ↑ N_2O), manure acidification (↓ NH_3), manure incorporation in soil and time of application (↓ N_2O), biofilters (↑ N_2O, ↓ NH_3)
# Authors' qualitative expert judgement based on available evidence presented in Section 6.2.2. Note that this is not a rigorous evidence synthesis or systematic review-based analysis and, as such, needs to be interpreted with care

Production-based mitigation strategies that optimise animal productivity while reducing emission intensities are essential for mitigating enteric CH_4 emissions in LMICs. Within these, climate-smart livestock practices that are triple wins – increasing productivity and incomes, incentivising reductions in livestock numbers and thereby reducing emissions, while supporting adaptation to climate change – need to be prioritised. For the majority of livestock keepers, especially in LMICs, the adoption of climate-smart livestock practices is the most cost-effective and often the sole practical strategy to reduce CH_4 emissions at the present time. Even here, upfront costs can limit their adoption. Mitigation strategies to reduce absolute CH_4 emissions are likely to play a greater role in HICs, as animal productivity is already high and mitigation through productivity gains is possible but will be limited. In HICs, emissions can also be reduced by shifting demand to plant-based alternatives (Willett et al., 2019) (see Section 3) and reducing meat consumption per capita, with meat produced in a more sustainable way.

The widespread adoption of mitigation technologies and strategies for livestock CH_4 emissions is hindered by a variety of barriers, such as lack of government policies and incentives, cost and financial constraints, regulatory barriers, limited awareness and knowledge of available mitigation technologies, technical complexity and feasibility, market access and consumer willingness to pay, social and cultural norms, infrastructure limitations and risk of rebound effect. To address these barriers, a multi-faceted approach involving financial support, policy interventions, consumer education and research is needed. International collaboration among all stakeholders is essential to overcome barriers, share knowledge and best practices, and promote the adoption of effective mitigation strategies.

Overall, the development and implementation of mitigation technologies and strategies for reducing livestock CH_4 emissions holds promise in contributing to global efforts to limit global warming, especially in the short term. However, these technologies and strategies need to be firmly placed in a broader pathway of change that focuses on a just transition to a more sustainable and efficient livestock sector, supporting dependent communities, with high animal welfare concerns, and accompanied by reduced consumption of livestock products where appropriate.

Organic cabbage plantation in the mountain of Gede Pangrango Sukabumi, West Java, Indonesia.
Ricky Martin / CIFOR

7

Agroecological Approaches

Core authors: **Jonathan Mockshell, Marcela Quintero, Manuel Ernesto Narjes, Sarah Jones, Wendy Francesconi**

KEY HIGHLIGHTS

- Agroecology and other sustainable approaches provide a transition pathway to achieving sustainable food systems.
- Leveraging agroecology approaches and enabling environment drivers offers a holistic set of principles.
- Implementing agroecology principles contributes to adaptation and mitigation co-benefits and builds resilience to shocks.
- Several barriers and knowledge gaps are limiting the potential to scale agroecology and other sustainable approaches.
- Increase investments, strengthen knowledge networks, foster market linkages, and reform policies and institutional frameworks for agroecology transition.

7.1 Setting the context

There is a strong consensus among stakeholders, as well as robust evidence, that agriculture needs to transition and transform to facilitate environmental conservation while maintaining or increasing overall productivity and achieving sustainable healthy diets (IPCC, 2022; HLPE, 2019). Agroecology and other sustainable approaches offer contextualised solutions to the adverse impacts on global food systems that humanity faces (including social and political instability) at the onset of the multiple crises of the Anthropocene Epoch (e.g., climate change and biodiversity loss). The latest review evidence shows that such approaches can help smallholder farmers adapt to climate change without yield penalties (Dittmer et al., 2023) and achieve food and nutrition security (Kerr et al., 2021). However, in some cases there are yield reductions in the initial phase of transitioning to agroecology and other sustainable approaches and recover overtime (Adamtey et al., 2016). The agroecology approach is best understood through a set of principles that are meant to guide transition and transformation to sustainable food systems. If applied properly, these principles can lead to systems that are environmentally sound, socially inclusive, and resilient to climate change and other external shocks. The principles include aspects related to the foundation of healthy agroecosystems (such as soils, animals and plants), biodiversity conservation, diversification of production and food systems, circularity and social inclusion, among others. The incorporation of these principles in the context of systems transformation is ultimately meant to change the way food is produced and how it reaches consumers.

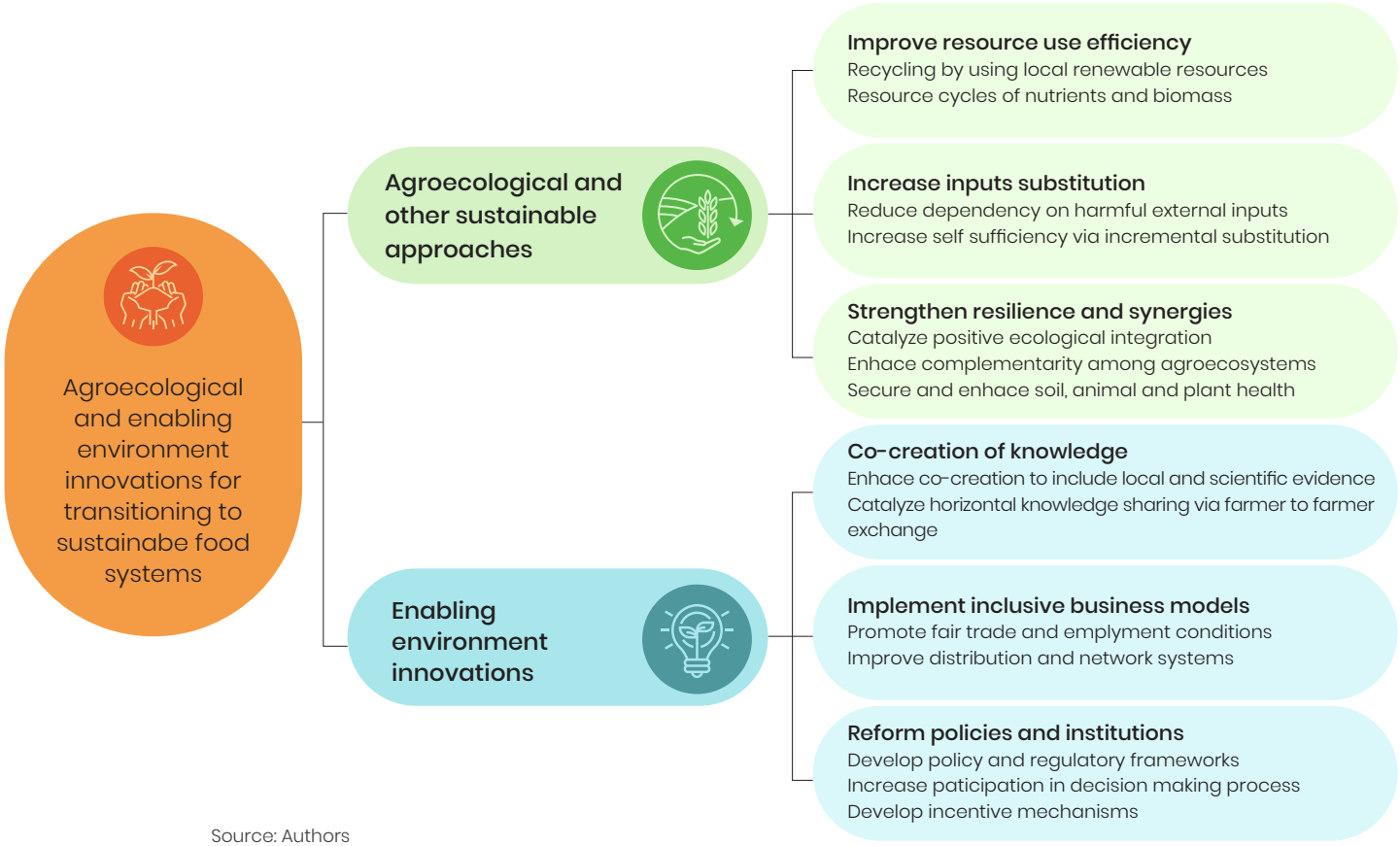
Guided by a set of principles (e.g., recycling, maintaining biodiversity and enhancing knowledge co-creation), agroecology aims at favouring natural processes that improve resource efficiency, strengthen resilience and secure social equity, while offering both adaptation and mitigation co-benefits to climate risks (HLPE, 2019). Beyond offering a set of sustainable practices and technologies, agroecology explores opportunities in institutional innovations (i.e., grounded on responsible governance and the circular and solidarity economy) that enable the required transformation of food systems to achieve food security and nutrition and climate resilience (FAO, 2018; Wezel et al., 2020). The transition to agroecology principles that encompass regenerative agriculture, conservation agriculture, climate-smart agriculture, sustainable rice intensification and organic agriculture practices leverages ecological and socioeconomic processes, from farm to fork, to mitigate and adapt to the changing climate (Mockshell & Kamanda, 2018). For example, agroforestry that incorporates agroecological principles, using diverse locally adapted varieties and breeds, and embedding natural habitats in agricultural farms and landscapes, works with natural processes to improve food security, nutrition, livelihoods, biodiversity, resilience and ecosystem services (FAO, 2015; IPCC, 2022). Also, keeping soil covered, maintaining minimum soil disturbance, integrating livestock, improving seed varieties and maximising crop diversity are innovative agroecological practices that contribute to building resilience and providing adaptation and mitigation co-benefits. While acknowledging that agroecology and other sustainable approaches contribute to a food system's adaptation capacity, climate change mitigation and resilience, the types of practices that work best are very context-specific, and appropriate solutions need to be co-developed with local farmers and public and private sector actors.

7.2 Strategies for agroecology and other innovative approaches

Agroecology and other innovative approaches provide a viable pathway to tackling climate risks and reducing anthropogenic GHG emissions from food systems. However, agroecology and other sustainable approaches must be bolstered by policy, and by institutional innovations that accelerate a just transition. These innovations consist of: (1) food system actor coordination that equitably leverages knowledge from all relevant stakeholders; (2) inclusive business models and markets; and (3) policies,

incentives and institutional innovations that spark behavioural shifts from farm to fork (Figure 7.1). Agroecological practices and technologies that are embedded in an enabling environment can improve productivity and incomes, while reducing emissions and safeguarding natural resources, building social cohesion, and adapting and building resilience across multiple levels and food systems (Place et al., 2022; Sinclair et al., 2019). Depending on the local context, there are trade-offs among the sustainability dimensions that influence the mitigation potential, adaptation capacity, yield, food security and social cohesion. This section examines the state of knowledge, barriers to implementation, gaps in scientific knowledge, and recommendations to enable transition to agroecology and other sustainable approaches in the face of prevailing climate risks, crisis and shocks.

FIGURE 7.1 **Agroecology and enabling environmental innovations for transitioning to sustainable food systems**



Source: Authors

7.2.1 Agroecology and other sustainable practices

Food systems are a major contributor to greenhouse gases affecting global climate change, and the agricultural sector is impacted by climate hazards (Dittmer et al., 2023). Agroecology and other innovative approaches have the proven ability to address climate risks, enhance the resilience of farming systems to climate change, and improve the flow of resources from diverse ecosystem services (Sinclair et al., 2019). Agroecology and other sustainable approaches emphasise the interconnectedness of components and levels within the agroecosystem and its wider socioeconomic context, aiming to optimise resource utilisation while reversing negative environmental impacts and empowering farmers, consumers and communities to secure just outcomes from their participation in the food system.

Sustainable production of flavoured cocoa in jungle region of Ucayali, Peru
Elizabeth Ramirez Perez / CIAT

- Changing farm-level practices is one step in the overall transformation to agroecological pathways. This transformation may encompass diverse types of transition pathways, depending on the point of departure in each context. As illustrated by Gliessman (2015), these pathways entail changes at various levels. Level 1 involves improved use of inputs that enhances productivity and inputs' use efficiency and reduces environmental damage. Level 2 involves substituting agrochemical inputs with bio-inputs – for example, adopting soil fertility practices to support a reduction in the use of chemical fertiliser by maximising the use efficiency of chemical fertiliser and substituting it for less damaging inputs to build resilience (Section 2). Level 3 is about redesigning agroecosystems, encouraging ecological interactions that generate soil fertility, nutrient cycling and retention, water storage and biological control of pests, among other improvements. In certain low-income settings, there could be an additional level (Level 0) to denote a starting point that is characterised by the lack of input use and low agricultural productivity, and where agroecology and other sustainable approaches can help enhance productivity by increasing the sustainable use of inputs and practices that maximise ecological interactions.
- The levels described above translate into proven agroecology and other sustainable practices. (1) Agroforestry: Agroecology encourages the integration of trees with crops and livestock, creating diverse and productive agroforestry systems. Trees provide multiple benefits such as shade, windbreaks, nitrogen fixation, carbon sequestration, and the provision of fruits, nuts and timber that increase farm income and productivity and build resilience to shocks (e.g., price fluctuations). (2) Biodiversity conservation: Agroecology fosters the preservation and enhancement of biodiversity within agricultural systems. This includes promoting the use of diverse crop varieties, and the protection of natural habitats and wildlife, safeguarding natural resources and increasing adaptation and resilience. (3) Soil health management: Agroecology and regenerative agriculture emphasises the importance of maintaining and improving soil health through practices such as organic matter incorporation, crop rotation, cover cropping, composting and reduced tillage. These practices enhance soil fertility, structure and water-holding capacity while minimising erosion and nutrient loss.

7.2.2 Knowledge co-creation and advisory systems

Knowledge co-creation and advisory systems for agroecological approaches involve collaborative platforms that bring together stakeholders – farmers, researchers, policymakers, civil society organisations and extension agents – to collectively generate and share knowledge on agroecology. The platforms aim at promoting environmentally friendly agricultural practices while considering local contexts, traditional knowledge, trade-offs (e.g., achieving environmental goals and yield targets) and synergies (e.g., maximising natural and human resource capacities).

- Citizen science-led initiatives. These involve the active involvement of citizens, including farmers, in scientific research. These approaches enable the collaboration of non-scientists in the collection, research design and interpretation of data, improving the way results are understood by actors and reducing data collection costs (Ebitu et al., 2021; Albagli & Iwama, 2022). In knowledge co-creation for agricultural innovation, citizen-led approaches enable the incorporation of knowledge from actors at multiple levels – farmers, extension agents, entrepreneurs and consumers – who live and operate within the agricultural and food system (Helenius et al., 2020). During the co-creation of innovations with extension agents and scientists, citizen science can help agricultural researchers and extension agents learn from farmers and social and cultural organisations about sustainable agriculture alternatives (Ebitu et al., 2021). Including 'champion farmers' who have successfully applied agroecology and other sustainable approaches in research and development creates a 'seeing is believing' phenomenon that could encourage other farmers to adopt the sustainable agriculture practices.
- Digital advisory for agroecology and other sustainable approaches involves leveraging digital technologies and tools to provide guidance and support to farmers and stakeholders in implementing agroecology and other sustainable approaches. An analysis by Daum et al. (2022) confirmed the relevance of digital tools for different stakeholders in Benin, Kenya, Nigeria and Mali. For example, digital tools serve as decision support systems that consider multiple variables, such as soil type, weather conditions, market trends and input costs in real time (Basso & Antle, 2020). A combination of user innovation systems emphasising the involvement of the end user (farmers) in technology development enhances the building of collective intelligence, using the evidence base to make informed choices to manage climate shocks, adapt and build resilience (Gkisakis and Damianakis, 2020) (see also Section 8).

7.2.3 Inclusive business models and markets

Level 4 of Glassman's framework emphasises connecting producers and consumers and creating an enabling business environment at both the supply and demand sides. This requires business models that increase access to affordable inputs of agroecology and other sustainable approaches and create a market for the products. The current business environment and business models align very much to conventional agriculture. Thus, examining the gaps and incorporating agroecological principles will be critical to transform food systems and build resilience. Through inclusive business models aligned to agroecological principles, producers' organisations such as cooperatives enable small-scale farmers to collectively achieve economies of scale, by pooling their human and capital resources to engage in value-adding activities and invest in technologies, reduce costs and risks, increase productivity and gain bargaining power. By reducing high transaction costs, producers' organisations further promote the integration of small-scale farmers in modern local and global markets, i.e., helping them meet challenges such as marketing, certification, standards and procurement procedures (Fernando et al., 2021). There are various forms in which business models link small-scale farmers to other food system actors. Inclusive business models, for instance, address

the bottlenecks that limit small-scale commodity-dependent food system actors' access to markets and resources (e.g., finance and technology) by stimulating their participation in local and global business partnerships (FAO, 2015; Rosenstock et al., 2020) and by increasing their share in value addition. Furthermore, they potentially generate and combine social and environmental values (Mark-Herbert & Prejer, 2018), for example by promoting the adoption of sustainable practices and technologies that are characterised by principles of agroecology and other sustainable approaches (e.g., the circular and solidarity economy and resilience), such as organic agriculture, agroforestry, regenerative agriculture and climate-smart agriculture. Business models may, for instance, address multiple Sustainable Development Goals (SDGs) by generating climate-smart value through the provision of, for example, climate information, rural advisory services (i.e., agricultural information, advice and training), seeds and inputs, and financial services. These potentially promote agricultural productivity and support the resilience of farms and farmer livelihoods and the mitigation of GHG emissions (Rosenstock et al., 2020).

7.2.4 Policies and institutions

Level 5 of Glassman's framework aims at reforming policies, rules, institutions, markets and culture for a food system based on fairness, participation, localness and justice. The transition to agroecology and other sustainable approaches involves implementing policies and institutions that support ecological and natural processes, leading to biodiversity conservation and the wellbeing of farmers and rural communities. Without the linkage to policies and institutions to remove disincentives and perverse policies, the much-needed agroecology transition may not happen (Sinclair et al., 2019; Place et al., 2022). Policies and institutions can be classified as: (1) compensation mechanisms for enabling transitions towards agroecology (e.g., subsidies to compensate yield reductions during the initial years of transitioning to agroecological farming, tax breaks, producer price support, etc.); (2) procurement policies, such as for school feeding programmes; (3) regulatory policies (e.g., regulation of markets and actors, national agroecology policies); and (4) institutional and organisation measures (see Place et al., 2022).

- Implementation of taxes on consumer preferences. Aiming to shift diets towards plant-based, agroecological and local foods, and improvements in technology, has become a necessary tool in the EU to meet food systems policy targets (Röös et al., 2022). In developing economies, such tax policies are a less preferred policy option. Innovative ecological carbon emission, soil erosion and water consumption taxes to finance the transition and conversion process to agroecology-based organic agriculture are gaining momentum (Mendoza et al., 2020). Carbon tax is promoted in the public debate as a major option to mitigate climate change by discouraging consumption of 'carbon-rich' commodities and promoting recycling, reuse, and innovation towards the production and consumption of 'carbon-poor' commodities (Tapia Granados & Carpintero, 2013). Without appropriate social safety nets and proper targeting, the corresponding high prices from taxes will hurt poor and marginalised groups. In addition, the effects of carbon tax and carbon credit policies on the sustainability of regional agroecosystems and net emissions of CO^2 from agroecosystems are receiving attention (Belcher et al., 2008). This can contribute to reducing emissions, providing alternative incomes to farmers, and safeguarding natural resources.
- Financial incentives, investment and support schemes. Governments and private sector stakeholders can introduce financial incentives, subsidies, grants and low-interest loans to support the adoption of agroecological principles (e.g., no-till and cover cropping) and other innovative approaches. These financial mechanisms, coupled with institutional land rights, can assist farmers in investing in sustainable farming methods such as organic inputs, agroforestry systems, water conservation measures, soil erosion reduction mechanisms and renewable energy technologies (Sinclair et al., 2019).

CASE STUDY 7.1

Cocoa agroforestry in Peru

Cacao (Theobroma cacao) farming represents the main source of cash income for millions of small-scale farmers worldwide. The sector plays an important role in many developing economies, but it is facing multiple crises, including low productivity and incomes, climate risks and a non-negligible role in deforestation. The importance of cacao production as a main livelihood for many small-scale producers along the Aguaytía river basin in Ucayali justifies focusing on this commodity and its value chain as an entry strategy for agroecology in the territory. CGIAR's Agroecology Initiative and its local partners emphasise the importance of addressing agroecology beyond the field scale, through a holistic approach. Rather than exclusively focusing on the cultivation of cash crops, this approach integrates agroecological principles at the farm and landscape scales (e.g., through the production of organic fertilisers, cacao–plantain intercropping, organic vegetable home gardens and native fruit tree-based agroforestry arrangements). At the same time, there is exploration of scaling opportunities that are relevant for the entire food system through institutional innovations, such as inclusive business models and financial mechanisms that are conducive to agroecological transitions. Through a stakeholder consultation process, the cacao agroforestry system provides a farm-scale strategy to diversify farm incomes (thus mitigating price and yield shocks) by incorporating tree species that yield additional products such as timber, fruits and medicinal plants. Cacao agroforestry arrangements additionally offer a reduced deforestation alternative to cacao plantations, which in the Peruvian Amazon have traditionally been established under the slash-and-burn system that drastically alters soil biodiversity and natural habitats. Cacao agroforestry systems additionally maintain productivity, or even increase cacao yields, by preserving the natural soil biota and controlling soil erosion, thus maintaining soil fertility, while sequestering and storing carbon.

Sources: Ruf et al. (2015); Arévalo-Gardini et al. (2020); Mortimer et al. (2018); Mattalia et al. (2022)

7.3 Metrics for measuring progress

Designing holistic metrics to examine performance and generate robust evidence can strengthen the quality of knowledge and decision support on which practices and technologies work, where, for whom, and how to implement them effectively. Traditionally, agrifood performance metrics have been dominated by productivity and financial measures. With the transition and transformation of food systems, holistic performance tools are needed that use indicators and metrics that capture all three dimensions of sustainability: ecological, social and economic (Gliessman, 2015; HLPE, 2019).

To monitor the performance of agroecological and other sustainable agricultural innovations, two types of indicators need to be collected. The first is the level of integration of the innovation, for example, on a gradient from zero to complete adherence to FAO's 10 agroecology elements or HLPE's 13 agroecological principles, while the second is the sustainability performance across environmental, social and economic dimensions. Existing tools designed to collect both indicator types include FAO's Tool for Agroecology Performance Evaluation (TAPE) (FAO, 2019c) and BioVision's

Camera trap for monitoring biodiversity, Java, Indonesia.
Mokhamad Edliadi / CIFOR

Farm and Business Agroecology Criteria Tools (F-ACT and B-ACT), among others.
TAPE, for example, measures the level of adherence to agroecology using a series of five-point Likert scale indicators aligned with each of the 10 agroecological elements. Users of the tool can compare the level of integration of agroecology at a single farm household through time, or across farm households, by calculating the average score across all the relevant indicators. Separately, TAPE measures sustainability performance across five sustainability themes: governance, economy, health and nutrition, society and culture, and the environment, using between 10 and 15 quantitative and qualitative indicators. For example, women's empowerment is measured using the Abbreviated Women's Empowerment in Agriculture Index (A-WEAI) developed by the International Food Policy Research Institute (IFPRI). Each of the performance indicators can be collected on a repeat basis for time series analysis and can be standardised using local and national benchmarks to compare performance across farm households. The indicators in TAPE can be adapted and applied at other scales, such as community or landscape level.
TAPE generates insights that governments and public actors may use for the adaptation and redesign of research and development programmes (FAO, 2019; Mottet et al., 2020). The limitations of TAPE, and of most other existing tools, include that applying a global tool to assess the performance of different contexts is challenging, and localisation is needed to meet context-specific objectives, ensure co-design and ownership, and adapt questions and responses to capture locally important issues (Namirembe et al., 2022). The CGIAR Agroecology Initiative is developing an approach to close this gap through embedding a localisation process into a holistic agroecology performance assessment tool, currently being tested in eight countries (*https://www.cgiar.org/news-events/news/the-measure-of-agroecology/*).

Adoption of agroecology and other innovative practices can contribute to all four breakthrough dimensions, with performance measurable through a range of indicators (Table 7.1).

A meeting of farmers interested in using solar power pumps, Bihar, India.
C. de Bode / CGIAR

TABLE 7.1 **Indicators and targets for monitoring performance of agroecology**

Dimensions of breakthrough	Indicators with baseline and target values
Sustainably increases agricultural productivity and incomes	No targets exist on sustainably increasing agricultural productivity and incomes through transitioning to agroecology. However, collecting data on whole system yields, for example by using land equivalent ratios, is important to provide an accurate assessment of yield changes, since focusing on single crop yields is inappropriate in diversified systems. Other valuable indicators for sustainable agriculture include the proportion of cropland under diversified farming systems, and the proportion of farmland with natural or semi-natural habitat. Global Biodiversity Framework Target 10 aims for agricultural land to be under biodiversity-friendly practices by 2030. Yield and income stability through time are other important indicators under this breakthrough dimension, as agroecological and other sustainable approaches can reduce production volatility and provide diversified income sources, reducing vulnerability to price fluctuations.
Reduces greenhouse gas emissions	**Indicator 1: GHG emissions from agriculture** **Baseline (2019):** 13 Gt CO^2e (IPCC, 2023a) **Target 2050:** <4 Gt CO^2e per year (Mosnier et al., 2023, based on Paris Climate Agreement, SDG13)
Safeguards soil, water resources and natural ecosystems	**Indicator 1: Soil carbon content** **Baseline (2018):** Global Soil Organic Carbon Stock for topsoil (0–30 cm) is 680 peta-grams **Target (2030):** 713 peta-grams, assuming 4‰ increase based on '4 per 1,000' initiative (FAO and ITPS, 2018) **Indicator 2**: **Natural vegetation cover** **Baseline (2019):** Approximately 56% of land is natural or semi-natural vegetation with low human impact (Jacobson et al., 2019). This would be higher if including natural vegetation cover on farms, such as hedgerows, fallow land, woodlots, grass borders and set-aside, but currently no data exist documenting on-farm coverage. **Target (2030):** No loss of natural land and at least 30% of degraded terrestrial land restored (Global Biodiversity Framework (GBF) Targets 1 and 2 (https://www.cbd.int/gbf/targets/), SDG 15, New York Declaration of Forests) **Indicator 3**: **Biodiversity-friendly agricultural land** **Baseline:** no data exist on the extent of biodiversity-friendly agricultural land. **Target (2030):** Agriculture, aquaculture, fisheries and forestry are managed sustainably through a substantial increase in biodiversity-friendly practices, such as agroecological and other innovative approaches (GBF Target 10 (https://www.cbd.int/gbf/targets/)). **Indicator 4**: **Sustainable freshwater withdrawals** **Baseline (2013):** 28% of cropland is water-stressed, defined as where the ratio of freshwater withdrawals to total renewable freshwater resources is higher than 40% (WRI, https://www.wri.org/insights/one-quarter-worlds-agriculture-grows-highly-water-stressed-areas). **Target (2030):** Sustainable freshwater withdrawals (SDG Target 6.4)
Adapts and builds resilience to climate change	No targets exist on adaptation and resilience building in relation to transitioning to agroecology. However, SDG Target 2.4 and GBF Target 10 call for a substantial increase in sustainable practices such as agroecological and other innovative approaches, which by design help to increase the resilience of agricultural and food systems through building natural and social capital and diversifying income sources. Promising indicators for increasing climate resilience through agroecology include: (1) the proportion of crop, livestock and fish populations that are local, climate-adapted breeds; (2) the proportion of farmland with diversified farming practices, water and soil conservation practices, or integrated pest or nutrient management, including intercropping, agroforestry, cultivar mixtures, cover crops and mulching; (3) the number of income sources; (4) access to social support networks; (5) the number of intermediaries between producer and consumer (local supply chains are less vulnerable to global shocks); and (6) crop insurance against weather-related shocks.

Source: Authors

7.4 Actors and change agents for the agroecological landscape

Many stakeholders are involved in the transition to agroecology and other sustainable approaches, in agenda setting, advocacy, coordination, funding, research and marketing. These actors can serve as change agents to drive the adoption of agroecological and other sustainable approaches from farm to fork. Table 7.2 highlights some of the main change agents involved in enabling agroecology transition. However, this list illustrates the actors with the broadest participation and is by no means an exhaustive list of actors.

TABLE 7.2 **Actors and change agents driving agroecology transition**

Role	Actors enabling agroecology transition
Long-term vision and action plan	International: UNEP, FAO, CGIAR National: relevant ministries (agriculture ministries/environment and climate change ministries), agroecology coalitions, EU, One Planet Network
Demand creation and management	International: UNEP, FAO, IFAD, World Bank Regional: various regional bodies, e.g., EU, African Union, G7, G20 Donors and foundations: FCDO, Rockefeller Foundation, EU, SDC, CIDA, BMZ National: relevant ministries and civil society organisations
Infrastructure and supply chains	Certification organisations: e.g., FAIR Trade Private sector producer organisations: e.g., Kaoka, Nestle, PepsiCo
Finance and investment	International: Green Climate Fund, IFC Impact investors: Acumen Fund, Appui au développement autonome (ADA)
Research and innovation	CGIAR and particularly Centers like the Alliance of Bioversity International and CIAT, CIFOR-ICRAF, CIMMYT, IWMI, IFPRI, IRRI and IITA. Institutions such CIRAD, GIZ, Wageningen University, University of Hohenheim, Michigan State University (MSU), Universidad Intercultural Maya de Quintana Roo, Universidad de Chapingo, University of California, Thünen Institute, Berkeley, Alliance Food Sovereignty in Africa (AFSA), La Sociedad Científica Latinoamericana de Agroecología (SOCLA), Universidade de Santiago de Compostela (USC), Swedish University of Agricultural Sciences (SLU), Coventry University, Asian Farmers' Association for Sustainable Rural Development (AFA)
Market structures	Private sector producer organisations (e.g., Kaoka, Nestle, PepsiCo), SMEs (e.g., Colpa de Loros, Curimana)
Standards and certification	Global GAP and its GRASP standard; FAIR Trade, various regional and national agencies which set standards
Trade conditions	WTO, UNIDO, UNCTAD
Knowledge, capacity and skills	CGIAR Centers, FAO, IFAD, UNEP
Social engagement and impact	Farmers' organisations at international and national level, e.g., NFU (USA); CGIAR and relevant research universities that undertake dissemination work, La via Campsina
Landscape coordination	FAO, IFAD, Agroecology Coalition, Coalition of Action for Soil Health, TPP, Global Soils Partnership, 4per1000

Source: Authors

Notes: This table lists examples of actors in the agroecology and other sustainable approaches landscape. The list is by no means complete. BMZ = Federal Ministry of Economic Cooperation and Development; CIAT = International Center for Tropical Agriculture; CIDA = Canadian International Development Agency; CIFOR-ICRAF = Center for International Forestry Research and World Agroforestry; CIRAD = French Agricultural Research Centre for International Development; GAP = Good Agricultural Practice; GRASP = Global GAP Risk Assessment on Social Practice; IRRI = International Rice Research Institute; IWMI = International Water Management Institute; NFU = National Farmers Union (USA); SDC = Swiss Agency for Development and Cooperation; TPP = Transformative Partnership Platform for Agroecology; WTO = World Trade Organization; UNCTAD = United Nations Conference on Trade and Development; UNIDO = United Nations Industrial Development Organization.

7.5 Barriers to implementation

Access to resources, knowledge intensity, policy bottlenecks and risk perception are among the barriers affecting the pathway to agroecology transition. The following section highlights the major barriers that apply in some situations.

7.5.1 Access to resources

Agroecology and other innovative approaches often require different inputs and resources compared with conventional methods. For example, agroecology emphasises the use of organic fertilisers, biological pest control and crop diversification. Accessing these resources – organic inputs and technical expertise – can be challenging for farmers, particularly those in resource-constrained countries. Limited access to credit, markets and appropriate infrastructure can also hinder the adoption of agroecology and other innovative practices. On-farm production of biological inputs will help to minimise this barrier.

7.5.2 Knowledge and management intensity

In low-income countries, farmers, policymakers and the public often do not have adequate knowledge of integrated farming practices, so are limited in their ability to adopt and implement agroecological practices (Mockshell & Villarino, 2019). This can partly be attributed to inadequate agricultural extension delivery systems, especially in areas where government extension services are understaffed and underequipped. Cultural barriers and limited information also influence the adoption of agroecology practices and slow change. In other cases, conventional farming methods have been heavily promoted and supported over the years, while agroecology has received comparatively less attention. This lack of awareness can lead to scepticism or resistance to adopting new practices. Labour availability is another major challenge. In areas where labour is scarce or wage labour is expensive, the adoption of labour-intensive agroecological practices can become unaffordable (Mockshell & Kamanda, 2018; Mockshell & Villarino, 2019).

7.5.3 Research and development

Agroecology is a knowledge-intensive approach that requires continuous research and development tailored to specific ecological contexts. Funding for agroecological research is often limited compared with conventional agricultural research. Agroecology emphasises co-creation and farmer-led innovation, which may not align with traditional research and extension systems.

7.5.4 Market demand and infrastructure

Agroecological produce often faces challenges in terms of market demand and infrastructure. Many conventional markets and supply chains are designed for large-scale, standardised production and may not readily accommodate diverse, smaller scale agroecological systems.

7.5.5 Risk perception during transition phase

Shifting from conventional farming to agroecology often requires a transition period, during which farmers may experience reduced yields or income until the agroecosystem reaches a stable state. The upfront costs and financial risks associated with transitioning to agroecology can deter farmers, particularly small-scale producers with limited resources. This transition phase can deter farmers from embracing agroecology and other sustainable approaches, especially when they perceive significant risks or uncertainty associated with the change. Yet a review study by Dittmer et al. (2023) for crop yield response during agroecology transition under different input categories suggests higher yields

for 63% of cases reporting yields, while a review by Sánchez et al. (2022) showed that diversified farming systems are, on average, at least as profitable as simplified farming systems.

7.5.6 Policy and institutional support

In many cases, existing agricultural policies, regulations and institutional frameworks are outdated and geared towards supporting conventional, input-intensive farming systems, which can serve as a disincentive towards adopting agroecology and other sustainable approaches ((Blesh et al., 2023). These policies often provide incentives, subsidies and infrastructure that favour industrial agriculture, making it difficult for agroecology to compete or receive adequate support (IPES-Food, 2016; (Ding et al., 2021). While many governments in sub-Saharan Africa aim to increase food production and reduce food importation, there are limited programmes to promote sustainable production practices such as soil health or agroforestry (Jayne & Rashid, 2013; Mockshell & Birner, 2015).

7.6 Recommendations for implementing agroecological approaches

To overcome the current barriers and create an enabling environment for agroecological transitions – towards more sustainable, healthy and resilient agrifood systems, enhanced biodiversity and improved livelihoods for farmers – access to resources, markets, knowledge creation, and policy and institutional support is critical (Sinclair et al., 2019; Place et al., 2022). This could be facilitated through international action to collect, standardise and share data on the impact of policies, investments and institutional arrangements, to enable cross-country learning and analysis to identify which actions increase access to critical resources and incentivise positive behaviour change.

7.6.1 Enhance investments in implementation of agroecological and other innovative approaches through international funding and repurposing agricultural subsidies

International development assistance should prioritise combining funding for agroecology and other sustainable approaches through multilateral development banks, regional development banks and national banks, to increase access to funding. Repurposing agricultural subsidies for funding agroecology and other sustainable approaches, along with other technological approaches discussed elsewhere in this report is recommended. We recommend that the PD, co-led by the World Bank and the UK government, should prioritise the formulation of concrete pathways for repurposing agricultural subsidies to transition to agroecology and other sustainable approaches. Action could include international collaborative research/policy dialogue, which could commission a white paper on repurposing subsidies to agroecology and other sustainable approaches, along with other climate-friendly technologies discussed earlier in this report. The white paper should particularly recommend ways of compensating small-scale producers for the initial risks, which include losses due to yield penalties. Such compensation should be treated as 'public goods' in nature as it offers positive externality. Involvement of the private sector is also needed, including through strengthening of initiatives like Regen10, an ambitious collective action plan to scale regenerative agriculture worldwide. Regen10 was launched at COP26 by the World Business Council for Sustainable Development (WBCSD) and 12 partners.

7.6.2 Enhance knowledge sharing and development of indicators and metrices by strengthening existing knowledge networks

There is already a solid evidence base for agroecology and other sustainable approaches; now the attention, incentives and investment need to swing towards how to implement the practices through adequate funding and capacity building (see Section 7.6.1). However, there are still knowledge gaps (see Section 7.7). We recommend strengthening existing knowledge networks and co-creating new networks that bring together all the relevant players in the field (see the list of stakeholders in Table 7.1) for sharing agroecology and other sustainable approaches at all scales – local, regional and global – and for developing indicators and metrics for tracking progress and success in implementation. For example, CGIAR, the French Agricultural Research Centre for International Development (CIRAD), UNEP, FAO, The Nature Conservancy (TNC) and BioVision, among others, can come together with NARES and use existing knowledge platforms such as the Agroecology Coalition and Transformative Partnership Platform for Agroecology (TPP) to co-create and disseminate best practices. The same coalitions and platforms can develop the indicators and metrics needed for tracking effective implementation of agroecology and other sustainable approaches through harmonisation of methods and tools. Improving knowledge creation via increased investment in research and development specific to agroecology and other sustainable practices is vital.

7.6.3 Develop market linkages and incentivise private sector participation through existing and new partnerships

Strategies for linking farmers to the market through collaboration between international financial institutions and the private sector should be implemented. International cooperation efforts should aim at strengthening producer organisations (e.g., building management capacities and promoting women's participation and leadership). International action can also focus on innovative contracts linking international and local buyers that can facilitate and allow bundling incentives such as market premium prices, technical support (e.g., advisory services) and access to inputs (e.g., organic fertilisers, biological control agents, etc.). Producer organisations should help small-scale farmers achieve the economies of scale needed to improve their access to finance, competitive funds, markets and bargaining power, and thus to invest their social capital and pooled resources in sustainable practices and technologies that are conducive to agroecological transitions, such as participatory guarantee systems that reduce the prohibitive entry barriers to certified organic farming imposed by third party certification schemes. Facilitating an inclusive business environment and market structures and building strong, accessible and competitive market linkages for agroecological products is essential (Tacconi et al., 2022; van der Ploeg et al., 2019; Arslan et al., 2022; Jones et al., 2022). SMEs supporting the transition can be provided with incentives to supply biopesticides, organic fertilisers and certified improved seeds. We recommend that players like WBCSD bring together private sector actors, research and knowledge organisations like CGIAR, FAO and UNEP, and specialised agroecological knowledge sharing platforms like the Agroecology Coalition and TPP to exchange best practices that are known to have been successful in supporting the development of local and regional markets, promoting fair trade practices, and creating consumer awareness about the benefits of products encouraging agroecological and other innovative approaches. Certification agencies (e.g., FAIR Trade) should aim at harmonising standards around the terms and products of agroecological and regenerative systems.

7.6.4 Strengthen the policy and institutional frameworks needed for the uptake of agroecological approaches through policy dialogues and documentation of policy best practices

Key international research organisations (e.g., CGIAR), international NGOs working on sustainable agriculture and food systems (e.g., WRI, CIRAD, FAO, TNC, BioVision), private sector companies interested in increasing their environmental stewardship (e.g., Nestle, PepsiCo Positive, Kaoka), the research working group of the Agroecology Coalition and TPP should work at bringing partners together for dialogue and fostering collaboration. High-level policies should aim at repurposing incentives towards the adaptation and mitigation attributes of agroecology and other innovative approaches, such as improving soil health and removing disincentives such as taxes on organic foods (Sinclair et al., 2019). Private and public sector actors need to develop and implement policies and institutional structures that support the transition to agroecology and other sustainable approaches (Altieri & Nicholls, 2012; Bommarco et al., 2013). This includes revising existing agricultural policies to include agroecology and other innovative approaches, providing incentives and subsidies for agroecological farming, and creating a favourable regulatory environment for agroecological inputs, techniques and markets (Mockshell & Kamanda, 2018; Mockshell & Villarino, 2019). We recommend that existing mechanisms such as the PD facilitate policy roundtables with countries to share best practices on the policy and institutional frameworks needed for upscaling of agroecological practices, and to facilitate cross-learning from other sector-specific stakeholders mentioned earlier. Table 7.3 summarises these recommendations.

TABLE 7.3 **Recommendations for scaling agroecological and other sustainable approaches**

Summary of Recommendations	Relevant partners for implementation	Recommendation applicable at levels		Themes*
		Domestic	International	
Enhance investments for implementation of agroecological approaches through repurposing existing agricultural subsidies and through funding from international financial institutions	PD for suggesting concrete ways of repurposing subsidies, and international financial institutions, MDBs and national governments for deliberating on ways of repurposing subsidies based on evidence	✓	✓	Theme 1
Strengthen existing knowledge networks and co-create new networks for sharing agroecological and regenerative agricultural innovations at all scales, and for developing indicators and metrics for tracking progress and success in implementation	CGIAR, UNEP, FAO, TNC, BioVision, Agroecological Coalition and TPP	✓	✓	Themes 2, 3, 4
Develop conditions for enhancing market linkages by bringing together private sector actors and research and knowledge organisations to exchange best practices that are known to have been successful in supporting the development of local and regional markets, promoting fair trade practices, creating consumer awareness about the benefits of agroecological products, and harmonising standards	WBCSD, Regen10, UNEP, FAO, Agroecological Coalition, TPP and FAIR	✓	✓	Themes 5, 3
Strengthen the policy and institutional frameworks needed for the uptake of agroecological approaches through policy dialogues and documentation of policy and regulatory best practices	PD, along with CGIAR, UNEP, FAO, TNC, BioVision, Agroecological Coalition and TPP		✓	Theme 2

Source: Authors

Notes: * Theme 1: Climate finance; Theme 2: Policies, regulations and innovations; Theme 3: Metrics, indicators and standards; Theme 4: Research and development and demonstration (RD&D); Theme 5: Private sector, markets and trade

7.7 Gaps in scientific knowledge

As shown in Table 7.4, despite the advancements in scientific knowledge at Levels 1 to 3 (see Section 7.2.1), there is a need for greater investment in the localisation of promising solutions to adapt them to context-specific cultural, political, economic and biophysical conditions, using action research methods and analysis of localised trade-offs. This is important to ensure ownership and sustained use of effective approaches that maximise benefits and avoid unintended consequences. As the evidence suggests, in some cases there are no penalties to yield and a positive contribution of agroecology principles to food security (Bezner Kerr et al., 2021; Dittmer et al., 2023), but in some cases there are yield reductions in the initial phase of transition (Adamtey et al., 2016). This mixed result suggests a gap in scientific literature that needs further research to understand the implications of agroecological principles on socioeconomic and environmental indicators. In addition, there remain large knowledge gaps on the contribution of Levels 4a to 4c (economic, market, businesses and policy) and Level 5a (increasing the participation of marginalised groups). More evidence is required to understand how economic paradigms in a territory and country change from a perspective of 'feeding any population at any cost' to a perspective of feeding a population within the parameters of sustainable diets, planetary boundaries and short food chain circuits (Helenius et al., 2020). Studies are necessary to determine the relative prices of food from agroecological food systems and food from conventional systems, and to identify alternative markets to position the higher environmental and social value of the former (Helenius et al., 2020).

Research is also needed to understand the extent to which markets for products developed through agroecology and other sustainable approaches constrain or enable consumer behaviour and impact the diets and nutritional status of both consumers and agroecological farmers (Bezner Kerr et al., 2021; Hough & Contarini, 2023). There is still a need to learn more about the cost-effectiveness of voluntary agri-environmental schemes (e.g., payments to influence the adoption of environmentally friendly approaches) (Niederle et al., 2020) and the role and efficiency of incentive programmes. In addition, more action-oriented research is necessary to better understand how to tailor and implement context-specific policies that comply with one or more principles of agroecology and other sustainable approaches (e.g., greater understanding of priority knowledge gaps for different country contexts) (Place et al., 2022). Robust evidence of the cost-effectiveness of agroecological and other innovative practices compared with the alternatives is lacking, and analysis of consumer choices with respect to agroecology requires in-depth insights (Sinclair et al., 2019). Strategies to design private and public sector incentive and investment packages with high potential to enable the adoption of agroecological practices for specific value chains are also limited.

The potential of digital tools for extension delivery and tracing products to increase transparency requires further research. Further, the political economy of agroecology and other sustainable approaches versus conventional farming needs to be unpacked (Peeters et al., 2020; Mockshell & Kamanda, 2018). Given the diversity of agroecological practices, research on holistic metrics focusing on policies, incentives, and institutional innovations and performance indicators will be necessary for providing evidence-based insights. Designing such metrics and embedding them into assessment tools will help close remaining knowledge gaps on how to create an enabling environment for transitioning towards agroecology and other sustainable approaches.

7.8 Conclusion

Agroecological approaches have the proven potential to address climate risks, build adaptation capacity, and enhance the resilience of farming systems to deal with climate change and multiple crises, while improving the flow of resources from diverse ecosystem services (Sinclair et al., 2019; Dittmer et al., 2023; Tamburini et al., 2020;). Sustainable agriculture approaches provide a transition pathway to transforming food systems. Leveraging agroecological and sustainable practices and enabling environment drivers offers a holistic set of principles for climate action. Implementing agroecology principles in all field, farm and food systems contributes to adaptation and mitigation co-benefits and builds resilience to shocks (Tamburini et al., 2020). Several barriers and knowledge gaps are limiting the potential to scale out agroecological approaches. To leapfrog the transition to agroecology and other sustainable approaches, practices must be coupled to (1) food system actors' coordination and cooperation, equitably leveraging knowledge from all relevant stakeholders; (2) inclusive business models and markets; and (3) policies and institutional innovations from farm to fork. A combined agroecology approach (as illustrated by Table 7.4) contributes to the four objectives of the Agricultural Breakthrough Agenda and provides huge potential to catalyse mitigation and adaptation co-benefits. While barriers such as access to resources, limited research and development, inadequate market demand and perverse policies pose challenges to agroecology transition, providing financial investments, education and awareness, smart policies and incentives and institutional frameworks is critical to fast track the transformation of food systems. This will require significant international cooperation among all actors and change agents in the Global South and Global North to urgently strengthen and reactivate collaboration and knowledge platforms (Tamburini et al., 2020). Enhancing investments, strengthening knowledge networks, fostering market linkages and reforming policy and institutional frameworks for agroecological transition are critical for transitioning and transforming food systems.

TABLE 7.4

Qualitative assessments of contribution of agroecological and other sustainable approaches across the four breakthrough principles

Sustainability dimension and agroecology transition level	Agroecological innovations: practices, technologies, social networks, business models, markets and policies	Increases agricultural productivity and incomes	Reduces greenhouse gas emissions	Safeguards soil, water and natural resources/ ecosystems	Adapts and builds resilience to climate change
ECOLOGICAL					
Level 1	(1) reducing water use, (2) reducing pesticide use, (3) reducing fertiliser use, (4) reducing energy consumption, (5) reducing waste (related to post-harvest production), (6) improving yield per unit of input (crops, meat and fish), (7) precision agriculture	Medium	Medium	Medium	Low to medium
Level 2	(1) cover cropping to improve soil conditions, (2) adding alternate amendments, (3) growing crops to build soil nutrients (green manure), (4) biological pest management, (5) cover cropping for pest management, (6) implementing other pest management practices, (7) planting perennials, (8) reducing tillage, (9) low-input or organic farming, (10) incentives for sustainable agriculture	Medium	Medium	Medium to high	Medium
Level 3	(1) selecting locally adapted crops, (2) incorporating non-crop plants, (3) implementing crop rotation (complex systems with two crops or more), (4) spatially diversifying farms, (5) agroforestry, (6) integrating crops and livestock, (7) improving grazing systems (rotational, regenerative), (8) protecting biodiversity, (9) protecting pollinators, (10) mitigating climate change (soil carbon sequestration or achieving net GHG reductions)	Medium to high	High	High	Medium
ECONOMIC, MARKETS AND POLICY					
Level 4a	(1) re-establishing the connection between producers and consumers through community, (2) enabling the business environment, (3) policy support and incentives	High	Low to medium	Low to medium	High
Level 4b	(1) access, availability and affordability of improved seed varieties, (2) policy incentives (e.g., subsidies)	High	Low to medium	Low to medium	Low

Level 4c	(1) land use efficiency (yield), (2) yield gap/ yield potential, (3) efficiency as a ratio (output per unit of input, e.g., water-limited potential), (4) land equivalent ratios, (5) farm or landscape productivity gap/ possibility frontier, (6) input use efficiency through precision farming, (8) labour productivity	High	Low	Low	Low
SOCIAL					
Level 5a	(1) increasing participation of marginalised groups (youth and women), (2) promoting food values, (3) promoting equity, (4) reducing exclusion, (5) livelihood support	High	Low	Medium	High
HUMAN					
Level 5b	(1) nutrition, (2) food security, (3) health	Medium	Low	Low	High

Source: Authors' expert judgement based on available evidence. Note that this is not a rigorous evidence synthesis or systematic review-based analysis and, as such, needs to be interpreted with care. Additional sources for the indicators: adapted from Gliessman (2016); DeLonge et al. (2016); Musumba et al. (2017); Mockshell & Kamanda (2018); Beillouin et al. (2021); Tamburini et al. (2020); Ewer et al. (2023).
Note: Scorings of high, medium and low are estimates based on the level of evidence.

Farmer, uses mobile phone apps to enhance her yields and get access to markets and labor.
C. de Bode / CGIAR

8 Digital services

Core authors: **Douglas Merrey, Ana Maria Loboguerrero**

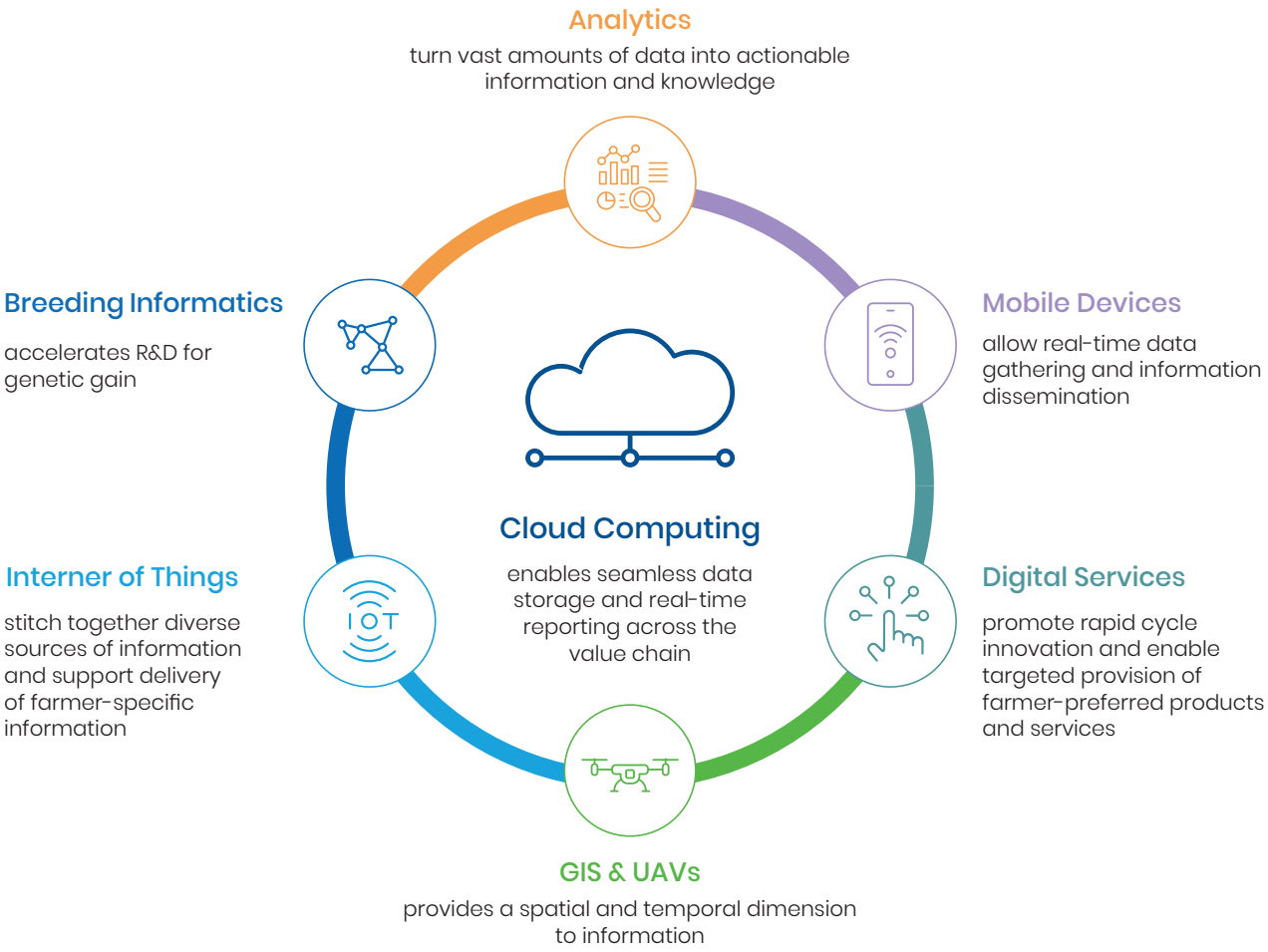
KEY HIGHLIGHTS

- Digital agricultural and climate services (DACS) have become critical tools in transforming systems at all levels.
- The gap between the Global North and Global South, as well as women and men, in access to DACS is very large because these services are often expensive and inaccessible for smallholder farmers.
- Where farmers have affordable access to DACS, they are benefiting from climate information, agronomic and marketing advice, and access to low-cost crop insurance and other services.
- Universal access to the internet and DACS is a critical pathway to educate smallholders and small businesses on ways to reduce the footprint of agriculture and achieve sustainable long-term food security.

8.1 The context

Digital services in agriculture (Figure 8.1) can help farmers and small agricultural businesses to rapidly gain the skills and knowledge they need to adapt to and mitigate climate change while improving food production sustainably in several ways (Weersink et al., 2018). Examples include optimising fertiliser use (Bacenetti et al., 2020), improving irrigation efficiency (Obaideen et al., 2022), improving livestock management (Mrode et al., 2020; Neethirajan & Kemp, 2021) and reducing food waste (Benyam et al., 2021). Digital tools can also help farmers increase production and profits by providing real-time data on crop health (Grimblatt et al., 2021) and weather conditions, as well as market prices (Fabregas et al., 2019). Widespread use of digital services will provide a unique tool to rapidly transform food systems.

FIGURE 8.1 **Digital Agriculture: A Pathway to Prosperity**

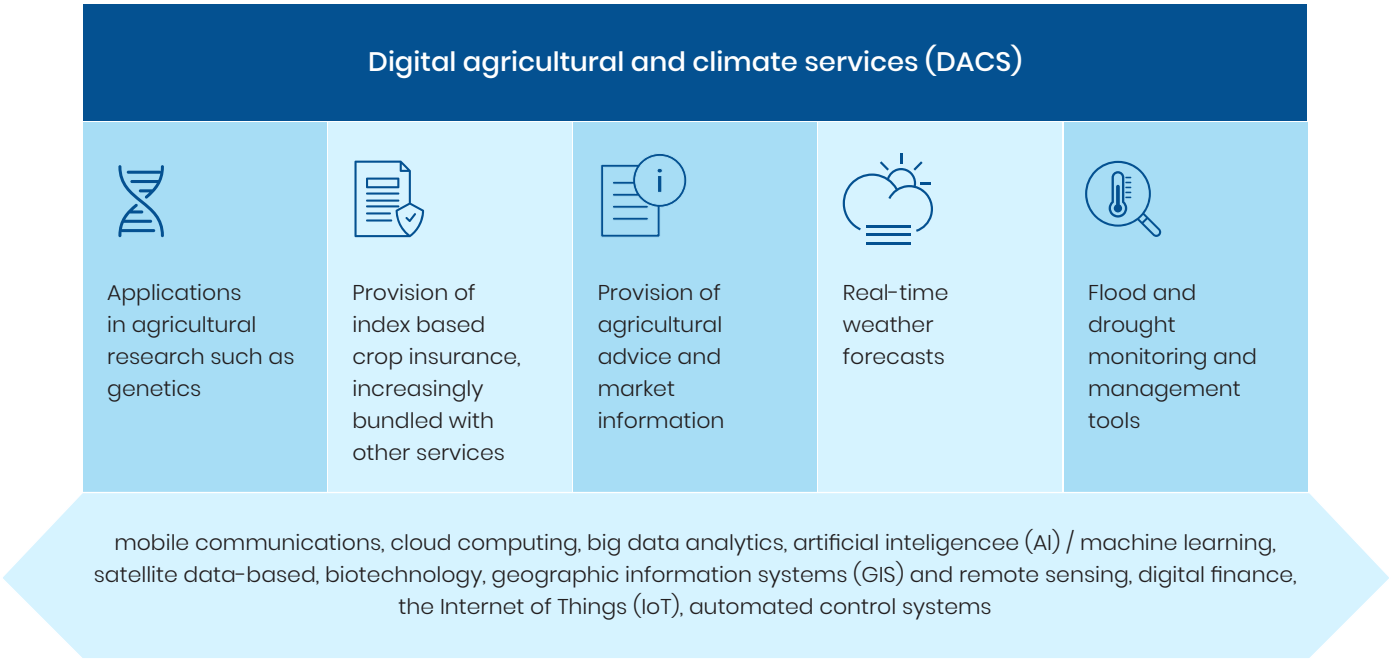


Source: CCAFS (*https://ccafs.cgiar.org/news/digital-agriculture-key-revolutionize-future-farming-africa*)

Digital services are increasingly being used throughout the agricultural value chain. Large-scale commercial farmers in the Global North have access to real-time data on crop water and nutrient requirements, weather forecasts and market conditions (McFadden et al., 2023; Lajoie-O'Malley et al., 2020; Saroniemi et al., 2022). However, digital agriculture technologies have high upfront costs, making it difficult for smaller farmers, even in high-income countries, to spread these costs over a large area. The digital divide between the Global North and Global South is even larger, with these services and equipment being too expensive and inaccessible for smallholder farmers (Nakalembe & Kerner, 2023). There are emerging concerns that this digital divide could contribute to slowing the achievement of several SDGs (Mehrabi et al., 2021).

While Digital Agricultural and Climate Services (DACS) are important everywhere, this section largely discusses their use in the Global South, where the need is greatest, focusing on five types of service that rely on digital applications (Figure 8.2): agricultural research, including genetic innovations; flood and drought monitoring and management tools; real-time weather forecasts; index-based crop insurance; and agricultural advice and market information, including apps that also offer training. Other digital services include improving product traceability, social protection programmes, financial inclusion and business-to-business e-commerce. The World Bank (2019) provides an overview of many of these applications, which are important but are at an earlier stage in the Global South.

FIGURE 8.2 **Digital agricultural and climate services**



8.2 Tools and technologies for digital agricultural and climate services

8.2.1 Digital applications for genetic improvements in crops and livestock

Van Etten et al. (2023) sketch out in detail how crop diversity research can benefit from a data-driven approach. Data-driven approaches that cross disciplinary and organisational boundaries can deliver new insights from multiple data sources, enabling greater interdisciplinary collaboration. Progress in machine learning enables more creativity and ways to extract value as well as an ability to accommodate complexity. Genomics and bioinformatics resources including genome sequencing and assembly are being used to accelerate crop improvement (Mochida & Shinozaki, 2010; Bevan et al., 2017). Examples of 'moon-shot' crop-breeding research projects are the *Artemis Project*, the *1000FARMS* project and the *Africa Dairy Genetic Gains (ADGG) e-learning tool*, which trains farmers in cattle breeding and health management practices. Basso & Antle (2020) point out that genetic improvement by itself is important but not sufficient for sustainable agricultural development.

8.2.2 Digital climate information and weather forecasting

Satellite-based climate information and management tools and real-time weather forecasts (e.g., rainfall, temperature) are two services that are based on the same technologies. They are discussed together in this subsection. Commercial farmers in the Global North have good access to the wealth of data and services available through cellular phone networks and the internet. However, in the Global South, there is a large gap between the demand and supply of climate and agricultural advisory services, and large gaps in actual use of these services, even when available (Ferdinand et al., 2021).

Several types of service are available using artificial intelligence (AI) and satellite earth observations (EO) (Nakalembe & Kerner, 2023). These include cropland and crop-type mapping; yield estimation; field-boundary delimitation; and pest, disease and anomaly detection. Simelton and McCampbell (2021) summarise the best-documented weather-based apps relevant for Southeast Asian smallholder farming systems, where both supply of, and demand for, such apps have been limited in contrast to access to phones. They document several opportunities to support agricultural management decisions.

Another AI–EO-based service is the provision of climate information, including the capacity to provide real-time weather and drought forecasts and accurate mapping of flood and drought areas (Amarnath, 2013; Amarnath & Rajah, 2015; Saha et al., 2021). For example, the South Asia Drought Monitoring System (*SADMS*) provides a weekly map of drought conditions at a spatial resolution of 0.5 km by 0.5 km in near real-time. Users can also download the drought maps, time-series plots of the areal extent and other data (Saha et al., 2021; Case study 8.1).

Burns et al. (2010) review both advisory and performance assessment digital tools that support agroecological transitions, including tools that measure impacts considering GHG emissions, toxic pesticides and inefficient nutrient use. These digital tools assess, at farm, landscape and value chain levels, the level and sources of GHG emissions and their mitigation, land-use changes and energy use; one tool (*ACE*) calculates GHG emissions from food loss and waste. Examples are the *Cool Farm Tool* and *CF-Rice*. The Cool Farm Tool has modules for measuring water footprint, soil carbon and biodiversity management to support farm- and field-scale management decisions. These tools are at an early stage of dissemination but hold considerable potential for the future.

8.2.3 Provision of index-based crop insurance and bundled services

Index-based insurance has emerged as an important digital service due to growing policy support, including in the developing world. A survey in 2020 found that 265 million crop insurance policies had been sold in the developing world, of which 80% were index-based. Many of these insurance products are being bundled with other services or inputs, such as fertiliser, seeds and pesticides (Kramer et al., 2022). For example, index-based crop and livestock insurance using satellite-based data to measure droughts, floods or affected crop areas is combined with the use of mobile phones to communicate with farmers and make payments (Hellin et al., 2017; Kramer et al., 2022). Examples include index based livestock insurance programmes in Kenya and Ethiopia and the CADENA (Componente de Atención a Desastres Naturales) programme in Mexico (Kramer et al., 2022; see also Hellin et al., 2017). This has drastically reduced the cost of providing agricultural insurance. In countries where climate data are limited, crowd-sourcing techniques through farmers' reporting of data present an opportunity for addressing climate risk (Osgood et al., 2018).

8.2.4 Provision of agricultural advice and market information

Agricultural extension in the Global South can benefit greatly from the use of modern ICT (Kieti et al., 2022; Mushi et al., 2022; Abate et al., 2023). However, while several pilot experiments are underway, they often fail to scale up. An exception is climate information services in Colombia, where the government has committed to advancing this agenda through policy documents such as its NDCs to the UNFCCC (Sotelo et al., 2020). There are several reasons for the lack of scaling out, including ineffective communication channels and a failure to incorporate the needs of user. A potential solution is to make greater use of radio and TV in addition to mobile apps to reach large numbers of farmers. For example, a reality TV show called Shamba Shape Up is being used to provide climate and agro-advisory services in Eastern and Southern Africa (Chilambe et al., 2022). Ortiz-Crespo et al. (2020) describe a case study from Tanzania of a successful digital agricultural service that used a co-design methodology to address smallholder farmers' different needs. In many countries, mobile apps provide farmers with real-time information on produce market prices, agronomic advice and even services such as ploughing (e.g., Hello Tractor). Examples include AgroMarketDay in Uganda and FarmConnecta in Botswana, which provide farmers with market information, weather forecasts, farming advice and micro-insurance. Esoko is a mobile and web-based platform that enables farmers to connect with buyers and sellers in their region (Nii-Koi, 2021). A study in India of digital agricultural services found that its use is positively and significantly associated with crop productivity, diversity and income (Rajkhowa & Qaim, 2021).

CASE STUDY 8.1

Climate information services and bundled crop index insurance

The South Asian Drought Monitoring System (SADMS) has been used to develop composite indices for floods and droughts. These indices combine rainfall data with satellite-based vegetation and temperature data, and are at the core of successful pilot programmes offering index-based crop insurance to small holder farmers (Saha et al., 2021, Amarnath et al., 2021, Alahacoon & Edirisinghe, 2022). From 2017 to 2021, nearly 15,000 households received flood insurance payments totalling USD 170,000 in Bangladesh, India and Sri Lanka. In 2021, Green Delta Insurance Company Ltd. scaled the index-based flood insurance product in Bangladesh and WRMS Pvt. Ltd. offered bundled services to 25,000 households. CGIAR scientists worked together with Oxfam and insurance companies to make the product available to the poorest farmers, including women, by overcoming barriers to uptake (IWMI, 2021; Amarnath et al., 2021; Aheeyar et al., 2021). CGIAR and partners disseminated climate advisory messages to over 35,000 households via mobile phone in Sri Lanka and India. They also piloted bundled services in India incorporating index-based weather insurance, climate resilient seeds, and weather and agro-advisory services to reduce farmers' risk in producing maize, wheat and rice (Kumbhat, 2020). These technologies are now ready to scale out and can significantly improve smallholder farmers' adaptive capacity in the face of climate change while enhancing livelihoods for women and youth.

Source: CGIAR Program on Water, Land and Ecosystems Annual Report, 2021 *https://www.iwmi.cgiar.org/archive/wle/research/annual-report/2021/index/*

8.3 Metrics for measuring progress

Metrics for monitoring access to and reliability and use of DACS, as well as its impacts, are required, but this topic is not well addressed in the scientific literature (Roussilhe et al., 2023). Companies and organisations providing DACS have their own performance indicators (Dittmer et al., 2022), but reliable assessments of the actual impacts of DACS on productivity, sustainable use of resources, changes in GHG emissions, effective adaptation to a changing climate and resilience in the face of challenges are lacking (e.g., Tsan et al., 2019). Some baseline data on the adoption of DACS exist, but are very rough and unreliable (Table 8.1). Further, these numbers are not disaggregated by technology and profiles of adopters. There are no internationally agreed targets for the adoption of digital services in agriculture. Coming up with such a target could be on the agenda for international collaboration in future Agriculture Breakthrough discussions among parties (Section 8.6).

TABLE 8.1 **Estimated data on DACS adoption in sub-Saharan Africa**

	Number/ percent	Other Notes
Cell/smart phone ownership	33M smallholders & pastoralists	Growing at 44%/year
% smallholders with internet access	<40%	24–37% of farms with <1 ha land; 74–80% of farms >200 ha
No. DACS providers	390	Source: Mehrabi et al., 2021
% registered actually using DACS	42%	15 of these have over 1 million users. 70% are youth; 25% are women
Estimated impacts based on only 50 data points, mostly self-reported	20–40% increase in yield or income	Bundled services self-reported yield increases 50–300%; income 20–100%

Source: Tsan et al., 2021, except where otherwise specified.

8.4 Actors and change agents for digital services in agriculture

There are many organisations working on various aspects of digital services in agriculture. They can potentially play important roles as change agents to help scale out strategies for reducing the digital divide and encourage the broad use of digital services. AIM4C Innovation Sprint includes a sprint on digital services: namely, digital resources for scaling up climate-informed agroecological transitions led by 15 organisations including the CGIAR and many of the organisations listed in Table 8.2, which lists potential key actors in this landscape. Section 8.6 suggests specific roles for the most important actors.

TABLE 8.2 **Actors and change agents in digital services for agriculture landscape**

Role	Agricultural and climate digital services actors
Long-term vision and action plan	FAO; ITU; Global Commission on Adaptation; Global Coalition for Data and Digital Food Systems Innovation; Food Systems 2030 (World Bank); GFAR; FARA; African Union
Demand creation and management	Researchers through pilot schemes; private and public extension services; NGOs; agricultural insurance companies; farmer organisations; mobile phone firms
Infrastructure and supply chains	National, regional and local governments; private sector including mobile phone firms
Finance and investment	Public mandate: governments, World Bank; regional development banks; IFAD; private digital service firms; foundations (e.g., BMGF); bilateral donors; national banks; rural micro-credit organisations; Bezos Earth Fund
Research and innovation	CGIAR; universities; GFAR; FARA; regional agricultural research associations (e.g., CORAF/WECARD; ASARECA; SADC-FANR)
Market structures	WBCSD; national governments; private firms
Standards and certification	ITU; FAO; national governments
Trade conditions	National governments; WTO; OECD; African Union
Knowledge, capacity and skills	CGIAR; universities; Alliance for a Green Revolution in Africa (AGRA); agricultural training institutions, DACS providers
Social engagement and impact	Smallholder farmers; farmers' organisations; International Initiative for Impact Evaluation for impact assessment
Landscape coordination	UN Climate Change High-Level Champions; Committee on World Food Security

Notes: ASARECA = Association for Strengthening Agricultural Research in Eastern and Central Africa; CORAF/WECARD = West and Central African Council for Agricultural Research; ITU = International Communications Union; SADC-FANR = South African Development Community Food Agriculture and Natural Resources.

8.5 Barriers to implementation

DACS have very high potential in the Global South, but serious barriers must be addressed to achieve its potential (FAO & ITU, 2022). The major barriers are limited infrastructure in rural areas; policy and institutional barriers; socioeconomic inequity limiting access; capacity barriers; and financial barriers.

8.5.1 Limited digital infrastructure in rural areas

The *CGIAR Initiative on Digital Innovation* and Ferdinand et al. (2021) estimate that over 600 million people still live outside the reach of mobile networks, and over 300 million smallholders lack access to digital climate services. Infrastructure limitations are a serious barrier to scaling out DACS (FAO & ITU, 2022; Mehrabi et al., 2021; Abate et al., 2023). Connectivity challenges (uneven or expensive coverage), unreliable or costly electricity, and fragmentation and weaknesses in digital platforms (e.g., no one-stop shop) are additional barriers (Kieti et al., 2022). But these barriers are as much a result of the other barriers discussed here as they are a cause of poor or unequal access.

8.5.2 Policy and institutional barriers

The FAO and ITU (2022) identify several policy-related barriers. These include a disconnect between ICT and agricultural policies and unfavourable policies for supporting agricultural entrepreneurs. Very few African countries have dynamic, supportive digitisation policies or regulatory frameworks. Examples include unsupportive banking/mobile money regulations in Senegal and Ethiopia, which contrast with more supportive frameworks in Kenya and Ghana (Abate et al., 2023). Kieti et al. (2022) identified the policy support needed for the marketing of agricultural produce online, to enhance market information and transparency, extend access to digital services to poorer farmers and provide more training, sensitisation and access to promote scaling out in Kenya. They also argued for regulatory support to encourage small-scale digital service providers to experiment and take risks. Unclear regulatory frameworks are also limiting the cross-border scaling of digital innovations (Abate et al., 2023). Other studies reinforce the importance of reforming policies, regulatory frameworks and laws to support scaling out DACS (e.g., Hellin et al., 2017; World Bank, 2019; FAO, 2021).

8.5.3 Gender and social inequity

The digital transformation of smallholder agriculture in the Global South is facing a major challenge due to unequal access to digital technologies and services (Rose et al., 2022; Shelton et al., 2022; Dittmer et al., 2022; Zhai et al., 2022; Mushi et al., 2022; Jarial & Sachan, 2021; Hackfort, 2021; Huyer et al., 2021; Mehrabi et al., 2021; Klerkx & Rose, 2020). According to the Global System for Mobile Communication Association (GSMA (2022)), about 264 million fewer women than men globally have access to the internet or a mobile phone, with the gaps being widest in South Asia and sub-Saharan Africa. Hackfort (2021) identifies four patterns of inequality in digital technology development: (1) distribution of benefits; (2) ownership of data and hardware; (3) digital literacy; and (4) problem-solving capacities. Extending DACS, such as index-based crop insurance, to women is especially challenging (Born et al., 2019).

Further, the top-down, corporate-driven nature of digital tools further disadvantages smallholders, and does not support social movements like agroecology, the sovereignty of local food systems and participants' self-determination. There are two serious challenges: unequal power relations, and a disconnect from farmers' needs and inputs (Shelton et al., 2022). Concerns about the lack of transparency and clarity around issues such as data ownership, portability, privacy, trust and liability in the commercial relationships governing digital agriculture are found in Europe, North America and elsewhere (Klerkx et al., 2019; Kieti et al., 2022; Warner et al., 2022).

8.5.4 Capacity barriers

The FAO and ITU (2022), World Bank (2019) and *CGIAR Initiative on Digital Innovation* identify insufficient digital skills, especially among women, youth and rural populations, as a serious barrier to scaling out digital services. In their exploration of the evolution of mobile-phone-enabled agricultural information services (m-Agri services) in Africa, Emeana et al. (2020) conclude that many of the services currently available are "highly likely" to fail or be abandoned because implementers are ignoring the literacy levels, skills, culture and demands of the users. To enhance the sustainability of m-Agri services, Kieti et al. (2022) recommend designing them with users and designing for scale and the long term, as do others (e.g., Ortiz-Crespo et al., 2020; Warner et al., 2022).

8.5.5 Financial barriers

Access to digital services is far too expensive for the poorest households in many countries, especially in sub-Saharan Africa. The global data baseline on access to mobile phones shows that only 24–37% of farms of <1 ha in size are served by third generation (3G) or 4G services, compared with 74–80% of farms of >200 ha in size (Mehrabi et al., 2021). Areas characterised by low yields, climate stress and food-insecure populations have especially poor service coverage. Farm households' internet access is very low in India (31%), Pakistan (21%), Tajikistan (12%) and Mexico (14%). In many African countries, fewer than 40% of farming households have internet access, and the cost of data is still prohibitive (Mehrabi et al., 2021).

This suggests serious challenges in expanding mobile phone coverage to smallholders; and identifying sustainable business models in view of limited paying capacity remains a challenge (Kieti et al., 2022; Abate et al., 2023). Additionally, inadequate investment in research and development is a major barrier to the accessibility, quality and effectiveness of DACS (FAO & ITU, 2022). As a result, the pace of digital innovation in the Global South is not being matched by the rate of agricultural transformation needed to support and sustain these digital technologies (Abate et al., 2023).

8.6 Recommendations for upscaling digital services in agriculture

Even without substantial government support, private firms are likely to provide DACS to well-capitalised commercial farmers, further exacerbating the already high degree of inequality. The fundamental challenge is to identify and implement measures that will level the playing field – i.e., make DACS available to poor smallholders, including women and youth. Building on the main barriers identified in Section 8.5, this section offers recommendations addressing international collaboration, policy, finance (for rural infrastructure), gender and social equity, and skills enhancement.

8.6.1 Foster international collaborative actions for scaling DACS through development of metrics to support governments and private sectors to reach out to small-scale producers

International collaboration must play a critical role in scaling out effective, equitable and affordable DACS to the 300 million or so smallholders who do not yet have access to such services. A lack of the common metrics and technical support needed to extend such services to smallholder farmers is an impediment. Therefore, we recommend development of metrics to monitor progress, and provide technical support for monitoring such indicators to governments and private sector start-ups so that they can reach out to smallholder producers. The ITU and FAO are well placed to jointly develop these metrics, in consultation with international and regional associations such as the GFAR, FARA and African Union. They can help by raising awareness and facilitating cross-country cooperation and sharing of experiences. The Global Commission on Adaptation, Global Coalition for Data and Digital Food Systems Innovation and CGIAR can provide research support to develop, test and disseminate methodologies and test cases for application of these metrics and indicators.

8.6.2 Improve policy coherence and support through international knowledge-sharing collaborations to generate evidence for action

Unsupportive and uncoordinated national policies were identified as a major barrier to private firms investing in providing DACS. We recommend that national governments, as signatories of the Agriculture Breakthrough, request that UN entities such as the FAO work with other partners to examine current policies in both the Global North and South to identify what works best, and then coordinate the development of a broad set of policy guidelines. The PDTSA, co-led by the World Bank and the UK

government, can also facilitate dialogues among governments to harvest and compile best practices on how to design and implement DACS for reaching out to underserved smallholder producers.

Special attention needs to be paid to encouraging PPPs to provide quality mobile internet and cellular services to smallholder producers, including women and youth, for them to make good use of DACS. Gender-aware inclusive design of digital programmes adapted to the local context can contribute to overcoming gender exclusion. Steinke and Schumann (2019) describe a "rapid inclusivity assessment tool" that can be used at the early design stage to achieve greater inclusion from the beginning (Dittmer et al., 2022). The World Bank's Food Systems 2030 initiative can provide analytical services and advice to interested countries (Voegele, 2023). We recommend that the Global Coalition for Data and Digital Food Systems Innovation work with FAO and CGIAR to examine policies in relation to five core principles: (1) building an inclusive digital revolution; (2) fostering data agency and responsible sharing; (3) being force multipliers; (4) innovating responsibly; and (5) sharing lessons learned.

8.6.3 Enhance investments through public and private finance, including through repurposing of agricultural subsidies and other domestic and international financial support

The Global Commission on Adaptation has co-developed a detailed blueprint for scaling out digital climate agricultural services to 300 million smallholders by 2030 (Ferdinand et al., 2021). The Commission estimates about USD 7 billion in investment by a combination of donors, private firms and governments can cover upfront investment costs and recurrent annual costs. The returns on DACS investments will be high, can drive GDP growth and offer income gains of upto 25% depending on product and geography (Ferdinand et al., 2021). In view of the availability of such detailed information, we recommend that international finance institutions such as the World Bank, IFAD and regional banks and donors commit sufficient funding to scale out equitable and useful DACS to smallholders in the Global South, including support for testing sustainable business models (Ferdinand et al., 2021; Kieti et al., 2022; van Etten et al., 2023); Abate et al., 2023).

We recommend that the PDTSA, co-led by the World Bank and UK, prioritise formulation of concrete pathways for repurposing agricultural subsidies to be invested in DACs. This can be achieved through facilitating multi-stakeholder dialogues based on the blueprint provided by Global Centre on Adaptation (GCA). Appropriate financial instruments should be developed to encourage private sector co-investment. Infrastructure investments include stable internet connectivity and bandwidth, wide mobile network coverage, secure server access and electrical power, as well as transport and storage facilities. Intangible investments should focus on the software – i.e., human capital and site-specific services. Concurrently, we recommend that countries in the Global South, with international financial support, develop competitive agricultural input and output markets and support services (Abate et al., 2023). The World Bank's Food Systems 2030 trust fund is designed to support the design, piloting and de-risking of PPP investments (Voegele, 2023). We recommend donors consider providing support through this trust fund.

8.6.4 Facilitate investment in RD&D and skill development through knowledge and information sharing on best practices

We recommend that bilateral donors, foundations, and governments invest in research to support the development and equitable scaling out of DACS as an integral component of enhanced investments in food system transformation. International collaboration is critical for success (van Etten et al., 2023). The *CGIAR Research Initiative on Digital Innovation* is collaborating with multiple partners

to develop and support transformative, equitable and sustainable digital innovations and can lead multi-stakeholder platforms to share best practices and gaps in research investments to guide action. We recommend that governments, with support from bilateral donors and foundations, both invest directly, and develop policies to encourage private sector investment, to develop a cadre of technical and professional ICT workers, develop entrepreneurial capabilities, and improve the human capital of farmers and rural entrepreneurs, with a special focus on women and youth. We recommend that governments build DACS skills into agricultural training institutes' curricula, and use videos, farm TV and radio shows as tools for raising awareness and delivering skills training to large numbers of rural people. Table 8.3 sums up the recommendations.

TABLE 8.3 **Recommendations for scaling DACS**

Summary of Recommendations	Relevant partners for implementation	Recommendation applicable at levels		Themes*
		Domestic	International	
Support development of metrics to monitor progress and provide technical support for monitoring such indicators to governments and private sector start-ups so that they can reach out to smallholder producers	ITU and FAO with support from GFAR FARA and research-based insights from GCA, Global Coalition for Data and Digital Food Systems Innovation, and CGIAR		✓	3 and 5
Create evidence for improving policy coherence and support through international knowledge-sharing collaborations to generate evidence for action in ways that are gender-aware and inclusive	PDTSA to facilitate dialogues, Global Coalition for Data and Digital Food Systems Innovation work with FAO and the CGIAR to generate evidence	✓	✓	2 and 4
Enhance investments through public and private finance, including through repurposing of agricultural subsidies and other domestic and international financial support	PD through facilitating a white paper on concrete ways of repurposing subsidies, and IFIs and MDBs for financing	✓	✓	2 and 1
Facilitate investment in RD&D and skill development through knowledge and information sharing on best practices that can be taken up by the private sector	CGIAR, Global Coalition for Data and Digital Food Systems Innovation, FAO and private sector	✓	✓	4 and 5

Source: Authors

Notes: * Theme 1: Climate finance; Theme 2: Policies, regulations and innovations; Theme 3: Metrics, indicators and standards; Theme 4: Research and development and demonstration (RD&D); Theme 5: Private sector, markets and trade

8.7 Gaps in scientific knowledge

Although researchers and private firms continue to refine DACS for commercial farmers in the Global North, this section focuses on knowledge gaps in the Global South. Five critical gaps in scientific knowledge are hindering scaling out DACS to smallholders in the Global South. These are: (1) using new digital tools to speed up research and its applications; (2) socially inclusive targeting of DACS; (3) providing real-time, accurate weather forecasting; (4) affordable bundling of DACS and other services and inputs; and (5) methodologies and metrics for assessing the impacts of the use of DACS.

van Etten et al. (2023) describe the potential for agricultural science, including crop breeding, to benefit from using large, diverse datasets and new analytical techniques to both speed up crop-breeding processes and target appropriate crop varieties for diverse agroecological conditions and cultural preferences. Another research innovation that remains to be explored is the potential application of AI systems including Large Language Models (a type of AI that uses statistical models to analyse vast amounts of data, learning the patterns and connections between words and phrases, which can mimic human intelligence).

A second critical scientific gap is identifying how to equitably scale out socially inclusive DACS to millions of female and male smallholder farmers. More research is needed to understand the local dynamics of gender exclusion and inclusion, social differences, social identity and other socioeconomic characteristics and the outcomes in terms of food security and incomes. Additionally, there are few or no examples of DACS reaching a sufficiently large scale and generating sufficient resources to be sustainable and able to continue developing (Ferdinand et al., 2021).

A third scientific gap is how to provide real-time accurate seasonal and weekly weather forecasts at local levels that smallholder farmers can rely on for making decisions, and how to generate accurate local-level index data on droughts and floods that crop insurance companies can reliably use for making payments. A related gap is knowledge of how farmers actually use such services in decision making (Born et al., 2021) and the best approaches for packing these in forms that can be better understood and consumed by local farmers and pastoralists. Improved weather forecasting services would benefit vulnerable smallholder farmers greatly, but this remains a work in progress (Aheeyar et al., 2021).

The fourth gap is how to scale out bundled services. Improved forecasts would facilitate scaling out of bundled services, such as weather forecasts, agronomic advice, index-based crop insurance, credit and provision of inputs (Amarnath et al., 2021)

Finally, there is a lack of methodologies and metrics for measuring impacts of digital services on agricultural outcomes. A recent study by Tsan et al. (2019) is one of the few that attempts to measure the number of digital agricultural solutions and their use and impacts, but far more work is needed.

8.8 Conclusion

Five types of DACS critical to transforming agriculture were reviewed in this section: agricultural research applications; flood and drought management tools; real-time weather forecasts; index-based crop insurance and bundled services; and agricultural advice and market information. These services are increasing rapidly and there is evidence of their positive impacts; nevertheless, an estimated 300 million smallholders still lack access to these services.

Five barriers need to be overcome: limited infrastructure; policy and institutional roadblocks; socioeconomic inequity; limited capacity; and insufficient finance. The section also highlights five science gaps: (1) applying digital tools to speed up research; (2) socially inclusive targeting of DACS; (3) providing real-time weather forecasting; (4) affordable bundling of DACS and other services; and (5) metrics for assessing DACS impacts (Table 8.4). The potential impacts are indirect – i.e., it is assumed that providing these services leads to changes in farmer behaviour.

TABLE 8.4 **Qualitative assessments of five types of DACS across the four breakthrough principles**

Type of DACS	Sustainably increases agricultural productivity and incomes	Reduces greenhouse gas emissions	Safeguards soil, water resources and natural ecosystems	Adapts and builds resilience to climate change
Agricultural research applications	High	Medium	Medium to high	High
Flood and drought monitoring and management tools	Medium to high	Medium	Low	High
Real-time weather forecasts	High	Low	Medium	High
Provision of advice and information	High	Medium to high	High	High
Index-based crop insurance (with or without other services bundled)	Medium to high	Low	Medium	High

Source: Authors' expert judgement based on available evidence presented in Section 8.2. Note that this is not a rigorous evidence synthesis or systematic review-based analysis and, as such, needs to be interpreted with care

Digital services are already transforming agriculture. They are ubiquitous in the Global North and increasing in the Global South. To achieve their transformational potential, we have four recommendations. (1) With international support, countries need to implement coherent cross-sectoral policies to support scaling out DACS. (2) International financial institutions and donors need to co-invest with national governments and the private sector to create the necessary infrastructure and technical capacities. (3) Policies, financial and information services, and capacity development need to

focus on minimising inequities between poor and wealthy farmers and between men and women. (4) International and national investments in research and development and skills development for both technicians and users need to be increased. Finally, international collaboration is critical for successful policy reform, scaling out investments, supporting equitable access to DACS, and implementing research and development.

DACS, particularly for smallholders in the Global South, are a critically important tool for promoting transformation of the global food system and improving productivity and natural resource conservation, reducing GHG emissions, and increasing resilience and adaptation.

Sun drying is the traditional method for reducing the moisture content of paddy. With sun drying the grains are spread out in the sun.
IRRI / CGIAR

9 Summary and way forward

Core authors: **Aditi Mukherji, Loraine Ronchi**

In this report, we have looked at seven technological areas where there are innovations that can be scaled up for achieving breakthrough in agriculture and food systems. These innovations span the various phases of food systems, from production to consumption. For example, clean fertiliser technologies ensure a reduction in emissions at the source; improved crop varieties are inputs to agriculture; innovations in fertiliser applications are implemented at the growing stage of crops; reductions in food waste and loss happen at all stages of the value chain; and shifts to alternative proteins and plant-forward diets happen at the stage of consumption. Similarly, each of the technological areas relates to different pathways for meeting the breakthrough goals (Figure 1.2): some, such as improving nitrogen use efficiency and low nitrogen fertiliser application in areas of high use, or the partial substitution of ASF with alternative proteins, help reduce demand for food and inputs in areas where use is unsustainably high; others, such as improved crop varieties, help produce more food without expanding into new agricultural lands; and yet other technologies lead to lower emissions and improved natural resources.

Given the overall focus of the Agriculture Breakthrough Agenda on international collaborative action, we are making recommendations across five thematic areas: namely, climate finance; policies, regulations and innovations; standards and metrics; RD&D; and trade and markets. The following are the five main recommendations, while Table 9.1 provides further details based on our deep dive into seven technological areas:

- **Recommendation 1:** Increased climate finance should be directed to supporting the deployment of agricultural technologies and approaches for which science has generated evidence on effectiveness, including agroecology, reducing food loss and wate, reducing livestock methane emissions, reducing emissions from fertilisers, and crop and livestock breeding.
- **Recommendation 2:** Governments, research institutions, international organisations and the private sector should commit to a long-term process to test, develop evidence and share learning on policy and implementation. This should prioritise the redirecting of subsidies to support agriculture to move towards sustainability and climate resilience, and the facilitation of faster uptake of proven technologies in the sector.
- **Recommendation 3:** Governments, international organisations and research institutes should develop common metrics and indicators to track the adoption of key sustainable agriculture solutions assolutions as well as to monitor the state of natural resources on which agriculture depends.
- **Recommendation 4:** Governments, research organisations and companies should work together to deliver higher levels of investment in agricultural research, development and demonstration, to be maintained over the course of this decade. Priority should be given to innovations that can reduce methane emissions from livestock, make alternative proteins a reliable and affordable option, increase the resilience of crops, and advance uptake of digital services by farmers.
- **Recommendation 5:** Governments should begin strategic dialogues on how to ensure international trade facilitates, and does not obstruct, the transition to sustainable agriculture. In addition to addressing the agricultural commodities that contribute disproportionately to deforestation, early priority should be given to agreeing standards, labels and regulations for alternative proteins, low emission fertilisers, and products of agroecological and other sustainable approaches, and to developing intellectual property frameworks that promote access to resilient and low emission crop and livestock varieties. This should be complemented with international sharing of best practice on mobilising private investment and engaging consumers.

The starting point of this year's report was the four principles of Agriculture Breakthrough proposed by last year's report (IEA, 2022). However, a modification of those principles was proposed, recognising the need for a just and equitable transition in this sector and the different geographical and socioeconomic contexts in which the four principles apply. Going forward, there are other dimensions that could be considered – for instance, around nutrition and the need for healthy, sustainable (low carbon) diets and the implications for human health (including antimicrobial resistance and zoonotic spillover issues), or issues of inclusion and social justice, particularly for smallholder farmers in the Global South. This year's report also delineated five clear pathways for achieving the breakthrough outcomes as enunciated through the four (modified) breakthrough principles. With two years of analysis behind them, the choices of technology areas and approaches, of breakthrough principles and of metrics to track these should be reviewed as part of the Breakthrough Agenda process for agriculture. Such a review is important to ensure that these breakthrough objectives, principles and pathways continue to reflect our evolving scientific understanding of how to bring about a just transition in the agrifood sector.

TABLE 9.1 **Recommendations for international collaborative actions across seven technology areas**

Recommendation	Summary of Recommendations	Relevant partners for colloboration
Recommendation 1 Increased climate finance should be directed to supporting the deployment of agricultural technologies and approaches for which science has generated evidence on effectiveness, including agroecology, reducing food loss and wate, reducing livestock methane emissions, reducing emissions from fertilisers, and crop and livestock breeding.	Incremental climate finance should be added to ongoing streams of development finance for **a greater integration of agroecological and other sustainable** approaches in farming and food systems that increase ecological functioning and enhance carbon storage and sequestration, while strengthening resilience to shocks. Reduction of **FLW** can be mainstreamed into all investments in food systems. The priority for support should be the scaling of specific ready technologies, particularly those that reduce **livestock methane emissions** and **fertiliser** production and application. Climate finance should support capacity building and technical assistance as cross-cutting elements. It should focus on the technologies and approaches that are ready to be assessed and packaged for scaling in specific geographic and socioeconomic contexts and where there is scientific evidence on their effectiveness.	IFIs, MDBs and climate-focused funds (e.g., Green Climate Fund)
Recommendation 2 Governments, research institutions, international organisations and the private sector should commit to a long-term process to test, develop evidence and share learning on policy and implementation. This should prioritise the redirecting of subsidies to support agriculture to move towards sustainability and climate resilience, and the facilitation of faster uptake of proven technologies in the sector..	For **livestock**, key international research institutes and industry leaders should foster knowledge sharing with national ministries and with the private sector to further the scaling of innovative technical solutions for reducing methane emissions and/or climate-smart livestock production practices that also improve livestock productivity and livelihoods – particularly for smallholder producers in LMICs. International collaboration should be strengthened, and knowledge exchange platforms developed on regulatory frameworks and policies on newer **alternative proteins** for countries with more limited engagement. Coordinated and increased technical assistance and data should be provided to existing multi-stakeholder platforms that are currently promoting dialogue among researchers, industry, governments and civil society on the needs and means to reduce FLW. Greater support should be provided to regional associations that raise awareness and to inter-country cooperation and knowledge sharing that is aimed at ensuring that poor people, women and youth have good access to mobile internet and cellular service. This can be achieved through the sharing of international experience on public–private partnership investments for affordable DACS and through increased funding to these regional associations. To complement incremental climate finance, platforms such as the PD should formulate concrete pathways for repurposing agricultural subsidies towards the financing priorities highlighted in Recommendation 1. Key agencies should document and disseminate policy experience and regulatory best practice to strengthen the policy and institutional frameworks needed for the uptake of agroecological and other sustainable approaches. Key agencies should create evidence to inform policy coherence and demonstrate the need for affordable digital services in agriculture that are gender-aware and inclusive.	GRA, CGIAR and WRI FAO, Codex Alimentarius Committee and WHO FAO, CGIAR, WRI, One Planet, and MACS-G20 Collaboration Initiative Global Coalition for Data and Digital Food Systems Innovation, working with FAO and CGIAR PD UNEP, FAO, CGIAR, TNC, BIOVISION and TPP Global Coalition for Data and Digital Food Systems Innovation, FAO and CGIAR

Recommendation 3 Governments, international organisations and research institutes should develop common metrics and indicators to track the adoption of key sustainable agriculture solutions assolutions as well as to monitor the state of natural resources on which agriculture depends.	An international agreement needs to be reached on metrics, measurements and reporting methodologies for **livestock** enteric methane emissions. Based on existing protocols, an agreement needs to be reached on the common adoption of globally consistent measurements for tracking **FLW**. Metrics for examining the performance of agroecology and other sustainable approaches (e.g., CSA and regenerative agriculture) should be agreed internationally to provide decision makers and would-be investors with accurate data. International collaborations should be promoted for developing common standards, metrics and labelling norms for different types of alternative proteins. The development of common metrics and indicators that monitor progress in reaching out to smallholder producers through digital services will inform technical support for governments and private sector start-ups and help ensure equitable DACS for all.	GRA, CGIAR, FAO and WRI FAO, UNEP, WRI, APHLIS and MACS-G20 Collaboration Initiative CGIAR, UNEP, FAO, TNC, BIOVISION, Agroecological Coalition and TPP FAO, EAT-Lancet Commission, GFI, WRI, CGIAR and private companies International Telecommunication Union and FAO
Recommendation 4 Governments, research organisations and companies should work together to deliver higher levels of investment in agricultural research, development and demonstration, to be maintained over the course of this decade. Priority should be given to innovations that can reduce methane emissions from livestock, make alternative proteins a reliable and affordable option, increase the resilience of crops, and advance uptake of digital services by farmers.	Further studies are needed to assess the specific on-farm mitigation potential and impacts of different methane emission-reducing strategies and technologies in the livestock sector in diverse regions and farming systems. Investing in RD&D to identify cost-effective MRV innovations and to estimate and monitor emissions reductions in the livestock sector could lead to greater carbon market opportunities, including for small producers. Research investments are needed with a long-term goal of making **alternative proteins** a reliable and affordable option both in HMICs, to replace high levels of ASF intake, and in LMIC contexts with high levels of malnutrition, to reduce child malnutrition using high-quality protein sources. Increased RD&D to advance the uptake of **DACS** should focus on: (1) the design of contextually appropriate DACS; (2) the identification of successful strategies for scaling and reaching poor smallholders; and (3) an assessment of the impacts of scaling DACS. Existing international collaborations should be strengthened to focus on new RD&D needs, such as the development of participatory protocols, including biocultural community protocols for future crop and livestock **breeding** for climate resilience (see Section 5.6).	FAO and CGIAR Global Research Alliance, CGIAR, FAO and WRI FAO, CGIAR, WRI and GFI, among others PD, Global Coalition for Data and Digital Food Systems Innovation, FAO and CGIAR to generate evidence CGIAR, FAO, UPOV and Codex Alimentarius Commission set up by WHO and FAO

Recommendation 5 Governments should begin strategic dialogues on how to ensure international trade facilitates, and does not obstruct, the transition to sustainable agriculture. In addition to addressing the agricultural commodities that contribute disproportionately to deforestation, early priority should be given to agreeing standards, labels and regulations for alternative proteins, low emission fertilisers, and products of agroecological and other sustainable approaches, and to developing intellectual property frameworks that promote access to resilient and low emission crop and livestock varieties. This should be complemented with international sharing of best practice on mobilising private investment and engaging consumers.	The development of market linkages for **agroecological** and other sustainable products (see Section 7.6 in this report) should include robust risk analysis and publicly supported risk instruments.	WBCSD, CGIAR, FAO, UNEP, Agroecology Coalitions and TPP
	In the **livestock sector**, technical assistance in training and capacity building is required to encourage the private sector to promote ready-to-scale methane-reducing technologies.	PD, GRA, CGIAR and WRI
	Public–private partnerships should be explored for value chain investments aimed at FLW management and awareness campaigns, and the scaling of DACS.	One Planet, FAO, MACS-G20 Collaboration Initiative, the private sector and relevant public organisations
	Common standards, metrics, labelling norms and common methodologies for assessments of environmental, social, health and nutrition impacts and for ensuring the overall food safety of **alternative proteins** should be established.	FAO, Codex Alimentarius Commission, ISO, GFI, WRI and CGIAR
	There should be international harmonisation of regulations, market standards and labelling for products such as new **low-emissions fertilisers** and new **alternative proteins** (e.g., microbial-based and cultivated meat).	GRA, INMS and INI (for fertilisers); WHO, FAO and Codex Alimentarius (for alternative proteins)
	International bodies should develop and/or enforce intellectual property frameworks that support recognitional justice and clearly set out the rights and responsibilities of the private and public sectors and those of international **crop-breeding** bodies and their local community partners.	CGIAR, FAO, UPOV and Codex Alimentarius Commission

Source: Authors

In conclusion, we must overcome the current path dependence that is leading to suboptimal outcomes in nutrition, environmental sustainability and GHG emissions, and we must push agricultural systems into new trajectories that reflect the vision of Agriculture Breakthrough. The technologies exist for doing this, but, given the high level of inequality characterising our agriculture and food systems, technological innovation by itself is not sufficient. What will be needed is the bundling of mutually synergistic technologies, policies and institutions aimed at transforming incentives at various levels of the food system. We will also need well-designed monitoring and evaluation systems to monitor the innovation ecosystem itself, to evaluate what is working, what are the bottlenecks, and what adjustments are needed. This includes having better metrics to assess and track progress in relation to the four dimensions of the Agriculture Breakthrough Agenda. So, one of the important elements of the future agenda will be to develop these metrics through international collaboration.

Acknowledgements

The CGIAR author team would like to express its sincere gratitude to the members of the Steering Committee for the Agriculture chapter, which comprised Ismahane Elouafi, Chief Scientist, FAO; Rebecca Brooks of the UN Climate Change High-Level Champions team; and Johan Swinnen, Managing Director of Systems Transformation at CGIAR and Director General of the IFPRI. The financial support of the FCDO is gratefully acknowledged.

We would also like to acknowledge all our colleagues who reviewed the report at various stages and provided valuable comments that went into improving the draft. They include Rachel Lambert and Áine McGowan from the FCDO; Simon Sharpe from the UN Climate Change High-Level Champions teamteam; Will Hall from the International Energy Agency; Preetmoninder Lidder from the FAO; Sophia Boehm, Mulu Gebremikael, Swati Hegde, Raychel Santo and Richard Waite from the WRI; and Giriraj Amarnath, Aniruddha Ghosh, Jawoo Koo, Rachel McDonnell, Frank Place, Jacob van Etten and Sonja Vermeulen, our colleagues at the CGIAR.

In addition, our deepest appreciation goes to the team of external expert reviewers who provided insightful comments. They were: Liam Brennan, Nicole Coombe, Ruth Davis, Ahmed Elkenawy, Andy Jarvis, Jekaterina Kopteva, Andreanne Leger, Pekun Oshadiya, Prajal Pradhan, Melissa Pinfield, Latifa Redani, Elliott Swartz, Leila Toplic, Jonathan Wadsworth, Paul Winters and Helena Wright.

Finally, sincere thanks also go to Ms Emma Bowa of the CGIAR for providing administrative and editorial support, without which this report would not have been possible.

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