Food and Agriculture Organization of the United Nations

THE IMPACT OF DISASTERS ON AGRICULTURE AND FOOD SECURITY

DIGITAL SOLUTIONS FOR REDUCING RISKS AND IMPACTS

2025

Required citation:
FAO. 2025. *The Impact of Disasters on Agriculture and Food Security 2025 – Digital solutions for reducing risks and impacts.* Rome. https://doi.org/10.4060/cd7185en

ISBN 978-92-5-140180-4

COVER PHOTOGRAPH © iStock/Qarlos Qastilla

SPAIN. Crop fields flooded by a storm.

THE IMPACT OF DISASTERS ON AGRICULTURE AND FOOD SECURITY

DIGITAL SOLUTIONS FOR REDUCING RISKS AND IMPACTS

2025

Food and Agriculture Organization of the United Nations
Rome, 2025

CONTENTS

TABLES

FIGURES

BOXES

FOREWORD

This report comes at a critical moment when the global community is confronting an era of unprecedented challenges to agrifood systems. The convergence of weather extremes, conflicts, economic shocks, and now the increasing frequency and severity of disasters threatens to prevent progress towards achieving Zero Hunger. This publication marks the second edition of FAO's biennial flagship series on disasters, reflecting the Organization's continued commitment to addressing these emerging threats. The evidence presented here is sobering: USD 3.26 trillion in agricultural losses over the past three decades, with annual damages increasing from USD 64 billion in the 1990s to USD 144 billion in recent years. These numbers reflect the struggles of billions of rural women and men whose livelihoods depend on agriculture.

The mandate entrusted to the Food and Agriculture Organization of the United Nations (FAO) by its founding members – to defeat hunger, eliminate poverty and promote sustainable use of natural resources – has never been more relevant or more urgently needed. This report demonstrates that disasters are not merely disrupting food production; they are systematically undermining the four pillars of food security: availability, access, utilization and stability. As highlighted in this report, when disasters destroy 4.6 billion tonnes of cereals around the world over three decades, lead to critical losses of energy and nutrients from the global food supply, and have the potential to disproportionately impact the most vulnerable populations, they strike at the very heart of our mission.

What distinguishes this report is its comprehensive approach to understanding and addressing these challenges. We have mapped how the impacts of disasters cascade through infrastructure, markets and ecosystems to perpetuate vulnerability long after the immediate crisis passes. We have quantified not only the economic but also the nutritional impacts of disasters, and the consequential loss of energy and nutrients from the food supply. We have also shed light on the hidden impacts in fisheries and aquaculture, a sector that provides livelihoods for 500 million people yet remains largely absent from disaster assessments.

Most importantly, this report recognizes the significant advances in digital technologies that are transforming agrifood systems, and focuses on digital solutions as the central theme for the current edition. The evidence shows that every dollar invested in anticipatory action can generate seven dollars in benefits for rural families. Digital technologies are already revolutionizing how we monitor risks, deliver early warnings and support farmers' decision-making. From the 9.1 million farmers now accessing parametric insurance through digital platforms to the communities using our early warning systems to evacuate 90 percent of at-risk populations before disasters strike, we are witnessing a fundamental shift from reactive response to proactive resilience-building.

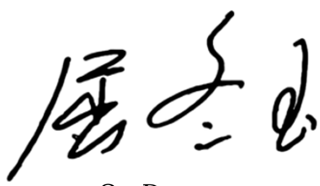
Yet technology alone is not the only answer. This report emphasizes that successful transformation requires putting farmers and fishers at the centre – designing solutions with them, not for them. It entails bridging the digital divide that leaves 2.6 billion people offline. It requires building institutions, developing capacities and creating partnerships that transcend traditional boundaries.

The four betters that guide FAO's Strategic Framework 2022–2031 – better production, better nutrition, better environment and better life – cannot be achieved without addressing the disaster risks that threaten agriculture. This report contributes directly to FAO's transformation agenda by providing the evidence base and practical solutions needed to build resilience at scale. It aligns with our Hand-in-Hand Initiative and the newly established Financing for Shock-Driven Food Crises (FSFC) Facility's commitment to using the best available data and technologies to support the most vulnerable, and with our dedication to leaving no one behind.

The findings presented here call for urgent action from all stakeholders. Governments must integrate disaster risk reduction into agricultural policies and investments. The private sector must engage in partnerships that ensure equitable access to digital innovations. Development partners must shift resources from emergency response to anticipatory action and resilience-building. And the international community must recognize that investing in agricultural resilience is not a cost but a foundation for sustainable development, peace and prosperity.

As we work toward the 2030 Agenda for Sustainable Development, time is running short. The window for building agrifood systems capable of feeding a growing global population while adapting to climate shocks is narrowing. Yet this report demonstrates that transformation is possible when knowledge, technology, and political will align with the wisdom and agency of farming communities.

I recommend this report to all who share our vision of a world free from hunger and malnutrition. Let it serve not only as a comprehensive assessment of challenges but as a catalyst for the transformative action needed to ensure that agriculture can fulfil its fundamental role: nourishing humanity while stewarding the planet for future generations.



Qu Dongyu
FAO Director-General

METHODOLOGY

The impact of disasters on agriculture and food security 2025 was prepared by the Statistics Division of the Economic and Social Development stream and the Office of Emergencies and Resilience of FAO.

Technical support was provided by the FAO Investment Centre; Office of Innovation; Office of Climate Change, Biodiversity and Environment; Fisheries and Aquaculture Division; Land and Water Division; Animal Production and Health Division; Natural Resources and Sustainable Production stream; Markets and Trade Division; Food and Nutrition Division; Agrifood Economics Division; Rural Transformation and Gender Equality Division; and Partnerships and UN Collaboration Division.

An advisory board consisting of experts from the collaborating divisions and offices of FAO guided the production of the report. The board approved the outline of the report and reviewed its analysis and technical content.

The report underwent a rigorous technical review by senior management, experts from various divisions and offices of FAO, as well as independent external reviewers. Finally, the report passed a process of executive clearance at FAO by the heads of the co-publishing divisions, the Chief Economist, the Deputy Director-General in charge of Emergencies and Resilience, and the office of the Director-General.

ACKNOWLEDGEMENTS

The impact of disasters on agriculture and food security 2025 is the outcome of extensive collaboration across several technical divisions and offices within FAO, primarily including the Economic and Social Development Stream, and the Office of Emergencies and Resilience (OER).

The report was jointly produced by the Statistics Division (ESS) of FAO and OER, with the overall guidance of Beth Bechdol and Máximo Torero Cullen, and under the direction of José Rosero Moncayo and Rein Paulsen. The development and production of the report was coordinated by Zehra Zaidi, the technical editor of the publication, with Part 3 coordinated by Wirya Khim. Technical and managerial oversight was provided by Piero Conforti and Fleur Wouterse.

Central to the development of the report were the technical papers and background materials prepared and revised by several experts. Valuable comments and final approval of the report were provided by the executive heads and senior staff of various FAO divisions.

Part 1 of the report was authored by Zehra Zaidi.

Part 2 of the report was authored and coordinated by Zehra Zaidi. In **Section 2.2.1**, the post-disaster needs assessment (PDNA) dataset was updated by Mahrukh Sarwar, with additional data processing by Ignacio Acosta at FAO. The C2 Sendai Indicator data was provided by Xuan Che of the UN Office for Disaster Risk Reduction (UNDRR), with support from Ignacio Acosta on the standardization and analysis of the dataset. The estimation of global disaster losses in **Section 2.3** was conceptualized and produced by FAO's Priti Rajagopalan, with support from Ignacio Acosta and key inputs from Nina Deliu (independent consultant). The quantitative estimation of nutrition losses was undertaken by Ignacio Acosta and Priti Rajagopalan, following a methodology developed by ESS and the Food and Nutrition Division. Victoria Padula de Quadros, Fernanda Grande, Giles Hanley-Cook, and Bridget Holmes of FAO also provided valuable inputs for this section. The analysis of losses in Fisheries and Aquaculture was based on inputs by FAO's Iris Monnereau and a technical background paper on the impact of marine heatwaves written by Salvador E. Lluch-Cota from the Centro de Investigaciones Biológicas del Noroeste (CIBNOR) with support from Arturo Yañez Arenas of the Center for Research and Advanced Studies of the National Polytechnic Institute (CINVESTAV), Daniel B. Lluch-Cota (CIBNOR) and Miguel A. Tripp-Valdez (CIBNOR).

Part 3 of the report was coordinated by Wirya Khim of FAO, with support from Phillip McKinney (independent consultant). Peer review was provided by Gerard Sylvester and Nikola Trendov of FAO, particularly on digital agriculture and innovation. **Section 3.1** was authored by Wirya Khim and Phillip McKinney with inputs from Gerard Sylvester. Jonathan Pound and Mario Zappacosta of FAO contributed inputs on the Global Information and Early Warning System on Food and Agriculture (GIEWS). Iria Touzon Calle (UNDRR) and Animesh Kumar (UNDRR) provided inputs on the DELTA Resilience System. The Climate Risk Toolbox was contributed by Hideki Kanamaru, Andrea Setti and Arianna Gialletti of FAO. Case studies on the 2023 El Niño and 2024–2025 La Niña events were contributed by FAO's Angela Kafembe, Andrea Amparore, Géraud Poueme and Josselin Gauny with input from Phillip McKinney and Wirya Khim. Inputs on SoilFER and WaPOR were contributed by Federica Chiozza, Rutendo Tadiwa Mukaratirwa, Alyne Spencer and Livia Peiser of FAO.

Contributions on agrometeorological advisory services were provided by Hideki Kanamaru of FAO, with inputs from Phillip McKinney and Wirya Khim. Inputs on the Smart Extension and Efficient Decision-making (SEED) Hub in Sri Lanka were contributed by FAO's Antonio Scognamillo, Sara Burrone and Kamran Khan Niazi. **Section 3.2** was authored by Wirya Khim with input from Phillip McKinney. Contributions on Foot and Mouth Disease (FMD), the Rift Valley Fever Early Warning Decision Support Tool (RVF-DST), Event Mobile Application (EMA-i), EMPRES Global Animal Disease Information System (EMPRES-i+) and Smart Markets were provided by FAO's Madhur Dhingra, Claudia Pittiglio, Fernanda Dorea, Filip Claes, Fabrizio Rosso and Nick Lyons. Input on the Fall Armyworm Monitoring and Early Warning System (FAMEWS) was contributed by Shoki Al-Dobai, Fazil Dusunceli, Maged Elkahky, Shawn McGuire, Kris Wyckhuys and Jean Claude Rwaburindi of FAO. Contribution on the Integrated Food Security Phase Classification (IPC) was provided by FAO's Kamau Wanjohi, Thomas Gabrielle and Sophie Chotard with input from Wirya Khim. Inputs on the Agricultural Monitoring Platform (AMP) for the Sudan were contributed by Abdullah Barhy and Livia Peiser of FAO. Jonathan Pound of FAO provided inputs on the Food Price Monitoring and Analysis (FPMA). Inputs on the Event Visualization in Emergencies (EVE) were contributed by FAO's Angela Kafembe, Andrea Amparore and Josselin Gauny with input from Phillip McKinney. Input on agricultural insurance innovation was contributed by Niclas Benni. Input on the Livestock Investment Rapid Appraisal (LIRA) was provided by FAO's Bruno Minjauw and Madhur Dhingra. Input on linking early warning to anticipatory action was provided by FAO's Niccolo Lombardi and Siphokazi Moloinyane. Contributions on social protection systems were made by Mark Johnson, Claudia Patrone, Federico Spano and Wirya Khim of FAO. **Section 3.3** was authored by Wirya Khim, Gerard Sylvester (CFIA) and FAO's Nikola Trendov, with input from Phillip McKinney. Contributions on human-centred design (HCD) and related case studies were provided by Van Lam Luong, Anna Müller, Berta Ortiz-Crespo, and Charlotte Schumann (Alliance Bioversity-CIAT). Matt Bjerregaard Walsh of FAO contributed a case study on digital solutions for transforming fisheries policies and management in the Philippines. FAO's Milica Petruljeskov, Adria Urso Coll, and Annamaria Pastore provided input on the FAO and Google Earth Engine Partnership case study. Input on FAO's Virtual Learning Centres (VLC) was contributed by FAO's María De la Puente Arévalo and Madhur Dhingra.

Part 4 was authored by Zehra Zaidi.

Several external experts provided comprehensive review and valuable technical comments for specific sections of the report. The entire report was technically reviewed by Giuseppe Forino (University of Salford).

The FAO Publications and Library Branch of the Office of Communications provided editorial support, design and layout, as well as production coordination for the In Brief version of this report in all six official languages. Daniela Verona and Olivier Lavagne d'Ortigue provided support on the design and presentation of report outputs. The FAO Meeting Services and Language Services branches of the of Governing Bodies Servicing Division (CSG) carried out the translations.

ACRONYMS

ACB	Agro-Climatic Bulletin
ADAM	Advanced Disaster Analysis and Mapping
Agromet	Agrometeorological
AHTU	FAO Animal Health Threat Update
AI	artificial intelligence
AMP	Agricultural Monitoring Platform
APIs	application programming interface
ASF	African swine fever
ASI	Agricultural Stress Index
BCR	benefit-cost ratio
CATI	computer-assisted telephone interviews
CGIAR	Consultative Group on International Agricultural Research
CH	Cadre Harmonisé
COP 16	Conference of the Parties to the Convention on Biological Diversity
CPI	consumer price index
CRTB	Climate Risk Toolbox
DAS	digital agriculture strategies
DELTA Resilience	Disaster and Hazardous Events, Losses, and Damages Tracking and Analysis
DIEM	Data in Emergencies
DINA	Drought Impact and Needs Assessment
DRM	disaster risk management
DRR	disaster risk reduction
EAR	estimated average requirement
EAS	extension and advisory services
ECMWF	European Centre for Medium-Range Weather Forecasts
EIOS	Epidemic Intelligence from Open Sources
EMA-i	Event Mobile Application
EMPRES-i+	EMPRES Global Animal Disease Information System
IFS	Integrated Forecasting System
EEZ	exclusive economic zone
EM-DAT	Emergency Events Database
ENSO	El Niño-Southern Oscillation
EVE	Events Visualization in Emergencies
EWS	early-warning systems
FAMEWS	Fall Armyworm Monitoring and Early Warning System
FARE	Fisheries and Aquaculture Response to Emergency
FAOSTAT	Corporate Database for Substantive Statistical Data

FAW	fall armyworm
FMD	foot-and-mouth disease
FPMA	Food Price Monitoring and Analysis Tool
GEEP	FAO–Google Earth Engine Partnership
GEOGLAM	Group on Earth Observations Global Agricultural Monitoring Initiative
GIEWS	Global Information and Early Warning System
GIS	Geographic Information Systems
GDP	gross domestic product
GLEWS+	Global Early Warning System for health threats and emerging risks at the human-animal-ecosystems interface
GPS	Global Positioning System
HCD	human-centred design
HiH	Hand-in-Hand initiative
ICT	information and communication technology
IoT	Internet of Things
IMEMS	Integrated Marine Environment Monitoring System
IPC	Integrated Food Security Phase Classification
ISS	information support system
IREY	Irrigation Reference to Enhance Yield
LIRA	Livestock Investment Rapid Appraisal
MCDA	multicriteria decision analysis
MFA	Major Fishing Area
MHEWS	multihazard early-warning systems
MHW	marine heatwave
ML	machine learning
MODIS	Moderate Resolution Imaging Spectroradiometer
MSME	micro-, small- and medium-sized enterprise
NDMOs	national disaster management offices
NDVI	normalized difference vegetation index
NHMS	national hydro-meteorological services
NSOs	national statistics offices
OCHA	Office for the Coordination of Humanitarian Affairs
PENCAS	Philippine Ecosystem and Natural Capital Accounting System
PDNA	post-disaster needs assessment
PPR	peste des petits ruminants
PRISM	Platform for Real-Time Impact and Situation Monitoring
RVF	Rift Valley fever

RVF-EW-DST	Rift Valley Fever Early Warning Decision Support Tool
SADC	Southern African Development Community
SEED	Smart Extension and Efficient Decision-making Hub
SIDS	Small Island Developing States
SME	small- and medium-sized enterprise
SoilFER	Soil Mapping for Resilient Agrifood Systems
UASs	unmanned aerial systems
UAVs	unmanned aerial vehicles
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNFCCC	United Nations Framework Convention on Climate Change
VAM DataViz	Vulnerability Analysis and Mapping Data Visualization
VLC	Virtual Learning Centers
WaPOR	Water Productivity through Open-access of Remotely sensed derived data
WFP	World Food Programme
WHO	World Health Organization
WMO	World Meteorological Organization
WMO-CHE	WMO Cataloguing of Hazardous Events
WOAH	World Organisation for Animal Health

KEY MESSAGES

➔ **Disasters have inflicted an estimated USD 3.26 trillion in agricultural losses over 33 years (1991–2023)**, averaging at USD 99 billion per year, with cereal crops bearing the heaviest burden at 4.6 billion tonnes of losses, followed by fruits and vegetables (2.8 billion tonnes), and with meat and dairy losing 900 million tonnes.

➔ **At a regional level, Africa is estimated to bear the highest relative burden at 7.4 percent of agricultural gross domestic product (GDP)** despite lower absolute losses. **Lower-middle-income countries face the highest relative losses at 5 percent of agricultural GDP**, exceeding both low-income countries (3 percent) and high-income countries (4 percent), revealing a critical gap where high exposure and vulnerability combine with limited resilient infrastructure.

➔ **Losses in production resulting from disasters correspond to a reduced availability of 320 kcal per person per day globally**, with iron losses corresponding to 60 percent of requirements for men and critical shortfalls in essential vitamins and minerals that have the potential to disproportionately affect vulnerable populations.

➔ **Marine heatwaves alone are estimated to have caused USD 6.6 billion in fisheries losses (1985–2022)**, with 15 percent of global fisheries affected and production losses exceeding 5.6 million tonnes, demonstrating the severe yet largely unmeasured impacts on aquatic food systems. Still, fisheries and aquaculture remain largely invisible in disaster assessments despite providing livelihoods for 500 million people.

➔ **Disaster impacts on agriculture extend far beyond immediate production losses** to include infrastructure damage, market disruptions, financial system failures and ecosystem service degradation that can persist for years after initial events. Current assessment tools must be extended to systematically capture both direct and indirect impacts and take into consideration non-economic values, differentiated effects on vulnerable groups, biodiversity losses and long-term ecosystem disruptions.

➔ **Digital technologies and tools are revolutionizing risk monitoring in agriculture**. Interoperable digital platforms transform raw climate, soil, socioeconomic and hazard data into actionable intelligence. Advanced analytics powered by artificial intelligence (AI) and machine learning (ML) now deliver integrated hyperlocal, real-time and actionable risk information.

➔ **Given their potential to reduce the risk and impact of disasters, digital solutions are critical for agrifood system resilience.** Data platforms bridge infrastructure gaps and allow for the timely and at-scale deployment of risk transfer mechanisms – for example, insurance or social protection. Advanced analytics help improve early-warning systems and design anticipatory actions.

➔ **Digital solutions allow for a shift from a reactive response to proactive risk reduction and prevention.** Improved access to real-time and actionable intelligence strengthens the ability of policymakers and farmers to take risk-informed decisions.

➔ **A digital transformation requires a comprehensive enabling environment.** Digital transformation succeeds when innovation is matched with sustained investment in capacity development, institutional strengthening and enabling infrastructure. Coherent policy frameworks are essential to scale and sustain digital solutions, ensure alignment with local priorities and create the conditions for long-term resilience building across agrifood systems.

➔ **Human-centred design (HCD) dramatically improves adoption and impact.** Digital solutions are most effective when they are co-designed with the communities they are supposed to serve – for example, smallholder farmers. Evidence shows that human-centred approaches significantly boost adoption and ensure that the benefits of digital innovation reach those most vulnerable and exposed to disaster risks.

➔ **Transformative disaster risk management in agriculture is driven by digital solutions that are embedded within strong institutions, supported by human capacity and enabled by robust infrastructure.** The most effective interventions combine innovation with sustained capacity building, participatory design, and alignment with existing systems to address multiple dimensions of risk and vulnerability.

➔ **Context-specific, adaptive approaches and strong multi-stakeholder partnerships are essential for successful digital solutions.** Tailoring tools to local conditions and fostering collaboration across government, research the private sector, civil society, and farming communities ensures scalable, interoperable, and sustainable impacts.

EXECUTIVE SUMMARY

PART 1. INTRODUCTION

Agriculture at the crossroads of crisis and innovation

The global agricultural sector stands at a critical juncture, facing an unprecedented convergence of disasters, while simultaneously witnessing remarkable advances in digital technologies that offer new possibilities for understanding, predicting and managing disaster risks.

The year 2023 began with the continuation of a severe multiyear drought across the Horn of Africa, affecting over 36 million people. Consecutive failed rainy seasons led to the death of over 13 million livestock in Somalia, Ethiopia and Kenya. Simultaneously, South America experienced one of its worst droughts in recent history, with the Amazon basin recording its lowest water levels in over a century, devastating crop production in Brazil, Argentina and Uruguay, with soybean and corn yields falling by up to 40 percent. Contrasting with these droughts, 2023 witnessed devastating floods in Pakistan, affecting 9 million people and destroying 849 000 hectares of crops. The El Niño phenomenon of 2023 also disrupted weather patterns globally, with drought affecting over 20 million people across Zimbabwe, Zambia and Malawi, and maize production falling by up to 70 percent in some areas.

The pattern has continued in 2024 and 2025, with biological hazards like African swine fever (ASF) devastating Asian pig populations, forest fires burning 3.24 million hectares in Canada by June 2025, and marine heatwaves (MHWs) disrupting fisheries and aquaculture. Conflicts in the Sudan and the Sahel displaced millions of farmers, creating agricultural collapse even in areas that experienced favourable weather conditions.

Yet alongside these mounting challenges, remarkable advances in digital technologies have emerged. Satellite technology, providing daily high-resolution imagery, has transformed agricultural monitoring capabilities. AI and ML algorithms process vast data to detect emerging risks. Mobile network expansion has brought connectivity to isolated rural communities, while financial technology innovations have made parametric crop insurance accessible to millions of smallholder farmers.

This report provides a comprehensive analysis of disaster impacts on agriculture and the role of digital innovations in transforming disaster risk management. It demonstrates that understanding disaster impact complexity is a prerequisite to developing effective solutions, and that digital innovations provide unprecedented capabilities for assessment and response.

PART 2. IMPACT OF EXTREME EVENTS ON AGRICULTURE AND THEIR MEASUREMENT

2.1 The complex nature of disaster impacts on agriculture

Contemporary agrifood systems face escalating pressures from disasters that extend beyond immediate production losses to encompass complex disruptions across entire agrifood value chains. The interconnected nature of modern agrifood systems means that a disaster affecting one component can trigger cascading effects through multiple pathways, often resulting in impacts greater than the sum of its parts. The vulnerability of agricultural systems is compounded by their exposure to multiple, often simultaneous hazards that create complex emergencies.

Understanding the transmission pathways and mechanisms of agricultural losses reveals that disasters affect agriculture through multiple interconnected channels. The most visible pathway occurs through direct disruptions to production systems, where extreme weather events destroy crops through physical damage and physiological stress, while livestock, fisheries and forestry systems experience mortality, reduced productivity and disease outbreaks. These primary impacts often trigger secondary effects, such as increased pest and disease pressure in weakened plants and animals, creating cascading consequences that extend beyond the initial damage.

Infrastructure destruction creates bottlenecks that amplify disaster effects throughout agrifood systems. When transportation networks are disrupted, farming communities become isolated from input suppliers and output markets. Storage and processing facilities also emerge as critical vulnerability points, with cold storage facilities being particularly vulnerable to power outages that can render high-value perishable products unusable within hours.

The financial dimension of disaster impacts creates additional layers of disruption by limiting access to credit, insurance and other essential financial services. Banking systems may experience physical damage or operational disruptions, insurance systems become overwhelmed by claims, and credit markets tighten as lenders become more risk-averse, constraining capital availability for both immediate recovery and longer-term adaptation investments. Market disruptions affect both input procurement and output marketing, with price volatility increasing as supply disruptions interact with speculative trading and emergency purchasing

A comprehensive understanding of disaster impacts requires recognizing both economic outputs that can be quantified in monetary terms and non-economic values that are harder to quantify but may be equally or more important for community welfare, cultural identity and long-term sustainability. Among the most significant non-economic losses are those related to cultural heritage, including traditional farming practices, Indigenous crop varieties and cultural landscapes that embody generations of agricultural knowledge accumulated through centuries of adaptation to local environmental conditions. The disruption of social structures, psychological and health impacts, and degradation of ecosystem services that support agriculture all represent critical non-economic losses that determine long-term sustainability and resilience.

Long-term climate shifts function as an overarching risk amplifier that intensify the onset of hazards, creating new risk dimensions that challenge agrifood systems and disaster management practices. Beyond increasing the frequency and intensity of extreme weather events, they push environmental conditions beyond critical limits for agricultural production, requiring shifts to heat-tolerant varieties or relocation of agricultural activities. Slow-onset events like persistent drought, desertification and sea-level rise represent particularly significant challenges that conventional disaster assessment frameworks often overlook, despite their potential to cause greater cumulative damage over time.

Limitations of disaster impact assessment frameworks include the omission of indirect impacts, long-term effects, and non-economic losses, especially social vulnerabilities and biodiversity and ecosystem losses. For example, women often bear disproportionate responsibility for food production, while having limited control over productive resources. According to FAO, rural female-headed households lose around 8 percent more income due to excessive heat events and 3 percent more due to floods. Indigenous and ethnic minority communities often remain invisible in standard assessment approaches, while biodiversity and ecosystem services impacts are rarely addressed despite their fundamental importance for agricultural sustainability.

2.2 Impact monitoring tools and gaps

The systematic measurement and documentation of disaster impacts provide essential evidence for understanding agricultural losses, yet current assessment approaches face substantial limitations that constrain our understanding of disaster consequences. Two principal tools available for monitoring disaster impacts on a global scale are the Sendai Framework Monitor and post-disaster needs assessment (PDNA).

The Sendai Framework for Disaster Risk Reduction 2015–2030 provides the primary global framework for monitoring disaster impacts and tracking progress towards reducing disaster risk. While agricultural loss reporting has expanded since the framework's adoption, with 87 countries reporting at least once under indicator C2 since 2015, the overall number of reports remains relatively low and has declined in recent years. Thus, the losses declared under the C2 indicator are informative but not necessarily representative of global agricultural loss trends due to inconsistent and under-reporting of data.

Although the reporting structure allows for disaggregated values for vulnerable groups, geographic areas and impact types, there is limited reporting by countries under these categories. Only 10 percent of countries have provided information on the type of hazard associated with reported agricultural losses, though available data points to the dominance of hydrometeorological events such as storms, floods, heatwaves and droughts in causing agricultural losses.

Post-disaster needs assessments are an international survey structure for comprehensive assessment of disaster impacts and recovery needs across multiple sectors. The PDNA methodology provides a harmonized approach for disaster impact assessment through standardized reporting mechanisms that capture damage to physical assets, losses in economic flows, human impacts on affected populations and recovery needs. Findings from 96 PDNAs undertaken during the 2007–2024 period in 63 countries show that agricultural losses make up an average of 23 percent of the total impact of disasters across all sectors.

Data from PDNAs indicate that while floods cause the greatest total economic damage to agriculture, droughts result in the highest proportion of loss within the sector – accounting for nearly 80 percent of agriculture's share of losses compared to other economic sectors. This finding is significant because droughts are typically underreported in disaster databases, and far fewer PDNAs have been conducted following drought-related disasters than after floods or storms. It is important to note that the PDNA survey constitutes a resource-intensive exercise requiring significant technical expertise, time, and financial resources that may not be readily available following major disasters when immediate response needs compete for attention and resources.

2.3 Global assessment and sectoral analysis of losses

In the absence of consistent historical datasets on realized disaster losses in agriculture, modelled estimations provide an alternative approach to understanding agricultural risk and vulnerabilities. The quantitative assessment presented in the report utilizes agricultural production data from FAO's Corporate Database for Substantive Statistical Data (FAOSTAT) combined with disaster event records from the Emergency Events Database (EM-DAT) to estimate losses for 191 agricultural commodities across 205 countries and territories from 1991 to 2023.

The results reveal disaster losses in agriculture totalling USD 3.26 trillion over 33 years, with nearly USD 2.9 trillion attributed to climate-related hazards, including floods, droughts and heatwaves. The data reveal three distinct phases: moderate losses in the 1990s averaging USD 64 billion annually; gradual increases throughout the 2000s reaching USD 67 billion per year; and a severe escalation from 2010 onwards with losses at USD 144 billion annually, amounting to an average annual loss of USD 99 billion over the last 33 years. Notable peak years include 2012 (USD 138 billion), 2019 (USD 173 billion), 2021 (USD 192 billion) and 2022 (USD 215 billion).

Physical production losses reveal that cereals are the most severely impacted commodity group with total cumulative losses of 4.6 billion tonnes, followed by fruits, nuts and vegetables (2.8 billion tonnes), and with meat, dairy and eggs losing 0.9 billion tonnes. Cereals exhibit significant variability in annual production losses, with substantial declines in 2012 (314.7 million tonnes) and 2013 (227.5 million tonnes), reflecting the sector's high sensitivity to climate variability.

Regional analysis demonstrates that Asia shoulders the heaviest burden at 47 percent of global losses (USD 1.53 trillion), reflecting the region's vast agricultural sector, large rural populations and heightened vulnerability to climate-related disasters. The Americas follow with 22 percent (USD 713 billion), while Africa accounts for 19 percent (USD 611 billion) – an amount with profound implications for food security, given agriculture's role as the primary source of employment and economic activity across the continent.

When losses are considered as a percentage of agricultural GDP, a dramatically different pattern emerges. Africa suffers the most severe relative economic impact at 7.4 percent of agricultural GDP, representing devastating impacts on economies where agriculture serves as the primary source of employment. The Americas follow with 5.2 percent, Oceania with 4.2 percent and Europe with 3.6 percent of agricultural GDP lost to disasters.

Analysis by country income groups reveals that lower-middle-income countries face the largest absolute losses, at USD 1.27 trillion, followed by upper-middle-income countries (USD 813 billion) and high-income countries (USD 766 billion). However, when assessed as a percentage of agricultural GDP, lower-middle-income countries suffer the highest relative losses at 4.7 percent, followed by high-income countries at 4 percent, indicating a critical vulnerability gap where countries have accumulated exposed agricultural resources but lack advanced disaster resilience systems.

Losses by hazard type show floods causing over USD 1.5 trillion in damages, representing the single most destructive hazard. Storms account for USD 720 billion, earthquakes USD 336 billion, droughts USD 278 billion, extreme temperatures USD 187 billion and wildfires USD 166 billion. However, amounts attributed to droughts and extreme temperatures likely represent a substantial underestimation due to systematic underreporting of these slower-onset hazards in the EM-DAT database.

Production losses significantly impact nutritional availability. They translate into estimated daily losses of approximately 320 kilocalories per person per day globally over 33 years, representing 13–16 percent of average daily energy needs. The analysis reveals iron losses corresponding to 60 percent of requirements for men and critical shortfalls in essential vitamins and minerals that have the potential to disproportionately affect vulnerable populations.

Fisheries and aquaculture face unique assessment challenges due to their direct dependence on natural ecosystems and location in vulnerable coastal areas. With 61.8 million people engaged in primary production and an estimated 500 million people relying on small-scale fisheries and aquaculture for livelihoods, the sector's importance is unique. Analysis of marine heatwaves reveals production losses exceeding 5.6 million tonnes and affecting 15 percent of fisheries between 1985-2022, with economic losses of nearly USD 6.6 billion.

PART 3. DIGITAL SOLUTIONS FOR DISASTER RISK REDUCTION IN AGRICULTURE – FROM INNOVATION TO IMPLEMENTATION

3.1 Digital technologies transforming agricultural risk management

Agriculture faces unprecedented challenges from increasingly frequent and severe disasters, fundamentally reshaping how we must approach risk management in the sector. Digital solutions serve as a conduit for transferring knowledge to multiple stakeholders and policymakers, empowering them to act through advanced analytical models that integrate multiple types and scales of data, including socioeconomic, soil health, climate, hazard and agricultural information. These technologies help overcome challenges by providing innovative solutions for improving access to advisory services, market linkages and facilitating access to credit through traceable means.

The growth of new technologies brings transformative opportunities for extension and advisory services, bridging information gaps between value chain actors, while contributing to fair trade, market accessibility and social participation. Location-specific, real-time and context-sensitive services help farmers tailor their agronomic practices based on weather patterns and market demands, with multichannel delivery through radio, television, mobile phones and the internet helping overcome accessibility challenges, including literacy barriers.

Digital tools for risk knowledge and monitoring have revolutionized data collection, analysis and granularity. FAO's Global Information and Early Warning System (GIEWS) provides regular data on factors impacting global food supply and demand, including near-real-time earth observation data on drought conditions through the Agricultural Stress Index and food price data across more than 120 countries. The UNDRR's new DELTA Resilience system standardizes data collection and analysis across sectors, ensuring consistency and comparability, while expanding monitored impacts to capture non-economic dimensions, including cultural losses, health, food security and biodiversity.

Remote sensing technologies enable rapid data collection before and after disasters, with advances in AI and ML enhancing geospatial approaches to disaster risk management. Google's GraphCast uses AI models to provide faster, more accurate global weather forecasts, while NVIDIA's Fourier Forecasting Neural Network delivers weeklong forecasts in less than two seconds. Cloud computing enables faster processing of vast datasets, representing one of the most significant advances in disaster risk knowledge.

FAO's Climate Risk Toolbox (CRTB) exemplifies integrated risk assessment platforms, providing an open-access resource that harnesses data from leading public providers across the United Nations system, NGOs, academia, the private sector and space agencies. The CRTB combines high-resolution geospatial data from climate, socioeconomic and environmental datasets into a single user-friendly platform, supporting evidence-based interventions and decision-making in over 200 projects. Risk mapping initiatives like the Data in Emergencies assessment ahead of the 2023 El Niño demonstrate how digital solutions address challenges of reliable, timely information for agricultural decision-making.

Digital advisory services are transforming how agricultural knowledge reaches farmers. The Soil Mapping for Resilient Agrifood Systems (SoilFER) project matches soil health data with fertilizer recommendations using extensive geospatial data to promote efficient fertilizer use and sustainable farming practices. Water management services address the critical challenge of sustainable resource use, with agriculture accounting for 70 percent of freshwater withdrawals. FAO's Water Productivity through Open-access of Remotely sensed derived data (WaPOR) project provides data to improve water management, while apps like Tunisia's IREY translate satellite data into actionable irrigation guidance.

Agrometeorological advisory services demonstrate significant economic benefits, with farmers in India reducing input costs by USD 29.65 per hectare for wheat and USD 44.48 per hectare for paddy rice. In West Africa, advisories improved farmers' incomes by USD 40–116 per hectare, depending on timing and location. Integrated platforms like FAO's Smart Extension and Efficient Decision-making (SEED) Hub in Sri Lanka deliver free geo-localized advisory services combining weather forecasts, crop management practices, market prices and agricultural advice, enabling 16 percent of farmers to set higher crop prices.

3.2 From early warning to resilient action

Digital technologies can support early-warning systems (EWS) that save lives and assets worth at least ten times their costs, with every USD 1 invested in anticipatory actions generating up to USD 7 in benefits in avoided agricultural losses. Disease surveillance and monitoring systems are one area where digital solutions have been leveraged for accelerating identification, reporting and diagnosis. FAO's and the World Health Organization's (WHO) collaborative platforms, including EMA-i+, Epidemic Intelligence from Open Sources (EIOS) and Global Early Warning System for health threats and emerging risks at the human-animal-ecosystems interface (GLEWS+), employ digital technologies that integrate multiple information layers to provide a better understanding of biological hazards. Similarly, FAO's World Reference Laboratory's OpenFMD platform facilitates global foot-and-mouth disease (FMD) surveillance through analytical tools that leverage genetic and epidemiological data. The Event Mobile Application (EMA-i) helps bridge the digital gap by supporting over 4 000 users in 15 low-income countries that have reported over 60 000 disease suspicions in three years.

Pest monitoring systems also showcase the transformative potential of digital applications. Following the fall armyworm's detection in Africa in 2016, FAO developed the Fall Armyworm Monitoring and Early Warning System (FAMEWS) with support from PlantVillage. This integrated system uses field scouting and pheromone traps with a mobile app for data collection, a cloud-based database, and a global platform for mapping and analysis. Since launch, FAMEWS has processed data from over 50 000 field scouting events and 16 000 pheromone traps across more than 60 countries, forming the foundation for advanced forecasting models and decision support tools.

Data integration tools can be used to strengthen early-warning systems for vector-borne diseases affecting agriculture. The Rift Valley Fever Early Warning Decision Support Tool (RVF-EW-DST) integrates real-time risk maps, historical data, and expert knowledge to provide monthly and eight-day risk updates for Africa. The tool combines climate data, livestock populations, human demographics and environmental factors to identify areas of potential risk. Since 2018, FAO has issued 19 Rift Valley fever (RVF) alerts in Africa, with successful applications in major outbreaks, including proactive vaccination campaigns that limited outbreak spread.

Food security monitoring has evolved through digital platforms like the Integrated Food Security Phase Classification (IPC), which provides a common scale for classifying food insecurity severity. The IPC's information support system enabled work to continue during COVID-19 lockdowns, allowing more analysis rounds, while reducing costs and speeding information processing. Integration with platforms like HungerMap Live and the Food Systems Dashboard demonstrates the power of data interoperability for comprehensive risk assessment.

Enhanced risk monitoring platforms provide granular, actionable insights for decision-making. The Sudan's Agricultural Monitoring Platform integrates comprehensive datasets, including land cover, climate indicators, flood history and socioeconomic data to identify vulnerable regions. Predictive analytics using machine learning and remote sensing enable crop yield forecasts months before harvest, as demonstrated during Southern Africa's 2024 El Niño drought, when FAO provided forecasts three months before harvest, enabling more effective impact assessments.

Near-real-time impact assessment leverages satellite imagery and AI for rapid damage evaluation. The World Food Programme's (WFP) PRISM platform integrates vulnerability data layers to prioritize populations exposed to climate hazards, while the SKAI application, developed with Google Research, enables building damage assessment 13 times faster and 77 percent cheaper than conventional methods. FAO's WaPOR platform provides high-resolution, spatially comprehensive data, which is useful for pre-disaster mapping, real-time monitoring and long-term recovery planning.

Linking early warning to anticipatory action demonstrates the transformative potential of digital solutions. In Somalia, during 2023's El Niño flooding, evidence-based early warning through the SWALIM flood model enabled FAO to deliver anticipatory actions, including flood defence infrastructure and evacuation planning. Ninety percent of at-risk populations were evacuated on time, while embankment rehabilitation held back flood waters for up to one week, enabling safe movement.

Digital innovations are revolutionizing agricultural insurance through parametric products that reduce costs and improve accessibility. Pula Insurance Advisors exemplifies this transformation, using digital registration systems, automated learning algorithms and rapid claim evaluation to insure 9.1 million farmers across 17 countries with USD 69.1 million in gross premiums covering 4.4 million hectares. Clients reported farm investment increases of up to 16 percent and yield improvements of up to 30 percent through combined insurance and advisory services.

Social protection systems increasingly leverage digital delivery mechanisms for disaster response. Kenya's M-Pesa facilitated USD 7 million in relief payments to 1.1 million beneficiaries during the 2017 drought, while Malawi's Social Cash Transfer Programme provided support to 74 000 households in 2022. Digital payments mitigate risks associated with physical cash disbursements, while significantly reducing transaction costs and providing audit trails that reduce corruption risks.

3.3 Mainstreaming digital solutions at scale

Mainstreaming digital solutions for disaster risk reduction in agriculture requires fundamental shifts in how we approach and address agricultural risk, demanding bold action, policy regulations and investments in key building blocks, including data governance, digital infrastructure, applications, enabling environments, capacity development and partnerships. Embedding human-centred design principles ensures digital tools create effective solutions that build long-term capacity for innovation, while empowering actors to efficiently address agricultural challenges.

Effective data governance provides the foundation for leveraging digital innovation, requiring accurate, accessible and interoperable risk-related data. The development of systems like the European Union's Integrated and Control Management System demonstrates how standardized protocols streamline data sharing and support comprehensive risk assessments. India's Digital Public Infrastructure for Agriculture integrates weather, soil and crop data in early-warning systems, while Indonesia's One Disaster Data Initiative streamlines data from various sources for disaster management. The UNDRR's DELTA Resilience system exemplifies how adopting common frameworks with scientifically agreed definitions and taxonomies enables better data integration, processing and visualization across borders.

Digital infrastructure requirements remain a critical challenge, with 2.6 billion people still offline globally despite significant progress in connectivity. Of these, 38 percent live within mobile broadband coverage but do not use it, while 5 percent lack coverage entirely. Addressing this requires energy solutions, connectivity expansion, device access, and efforts to overcome socioeconomic challenges through context-specific, linguistically appropriate and economically viable solutions.

Farm Radio International's combination of radio broadcasts with mobile and interactive voice response systems demonstrates how to reach farmers with limited internet access in remote areas.

Policy frameworks and strategies play crucial roles in mainstreaming digital solutions. National digital agriculture strategies foster agrifood system transformation by integrating technology, data and innovation. Madagascar's Digital Transformation Strategy for Agriculture 2024–2028 aims to improve food security and farmers' incomes through digital technologies for all, including satellite imagery, mobile applications and data analytics. Rwanda's strategy aligns with its Strategic Plan for Agrifood Systems Transformation, incorporating disaster risk reduction through four key areas: service digitalization, data-driven decision-making, digital competence development and adoption of emerging technologies.

Financing and partnership models ensure the long-term sustainability of digital solutions. Public–private partnerships, donor funding, blended finance models, and tiered pricing ensure accessibility and scalability. India's Digital Agriculture Mission commits public funding in partnership with private sector delivery, while companies like Pula leverage technology partnerships to develop climate insurance solutions bundled with agricultural inputs. The FAO-Google Earth Engine partnership exemplifies effective collaboration, training over 500 individuals in Ethiopia, Viet Nam and the Plurinational State of Bolivia, while providing 1 500 people, including farmers and vulnerable communities, with access to critical data and tools for managing agricultural risks.

Implementation experiences from countries provide valuable lessons. The Philippines' transformation towards ecosystem-based governance through its Integrated Marine Environment Monitoring System demonstrates how digital solutions enable evidence-based resource management. The system integrates bathymetric data, real-time environmental monitoring and community reporting to create comprehensive management frameworks. The GEOVS platform was identified as the most suitable for integrating real-time environmental data, enabling natural resource management agencies to make informed decisions, while requiring ongoing scaling and investment in capacity development.

Capacity development and digital literacy emerge as critical enablers of transformation. In Barbados, FAO strengthens extension services through precision agriculture, providing accurate data for crop management decisions. In Grenada, FAO supported the creation of a drone mapping and Geographic Information Systems (GIS) team for improved agricultural data collection and flood communication. Bangladesh's Cyclone Preparedness Programme trained 76 020 volunteers (50 percent women) to disseminate early warning and coordinate cyclone response. Educational initiatives equip farmers with knowledge and skills for implementing effective disaster risk reduction practices, including sustainable farming techniques, soil conservation, water management and crop diversification.

Human-centred design principles ensure digital solutions truly serve user needs by prioritizing empathy, inclusivity and iterative design throughout development. The process follows five key stages: scoping to define problems and goals; exploration to understand user contexts; creation of prototypes based on insights; validation through user testing; and implementation to ensure effective deployment. Organizations implementing HCD require institutional commitment, capacity building, cross-disciplinary collaboration, iterative feedback loops, and sufficient resources for prototyping and long-term monitoring.

Practical applications demonstrate HCD's transformative impact. In Rwanda, usability testing of a diet quality survey revealed significant barriers that, once addressed, improved completion rates from 58 to 70 percent, with women's rates reaching 76 percent. The SEED Hub's development through an HCD approach with local stakeholders ensured context-specific information addressing local needs, while leveraging existing institutional expertise. These examples highlight how HCD not only creates effective tools but builds long-term capacity for innovation, empowering farmers, researchers and communities to effectively face agricultural challenges.

PART 4. CONCLUSION

Charting a path forward for disaster risk reduction in agriculture through digital innovation

The convergence of escalating disaster impacts on agriculture and the emergence of transformative digital technologies represents a defining moment for global food security and rural livelihoods. The proliferation of remote sensing capabilities, AI, Internet of Things (IoT) sensors, and mobile communication platforms creates unprecedented opportunities for understanding, predicting and responding to disasters.

However, implementation experiences also reveal significant challenges that must be addressed for digital transformation to achieve its full potential. The digital divide remains a persistent barrier, with 2.6 billion people still offline globally, and many more lacking the digital literacy, devices or financial resources to effectively utilize digital services. Rural areas where most agricultural production occurs face particular challenges, including limited connectivity, unreliable electricity and inadequate digital infrastructure. These technical constraints are compounded by human capacity limitations, as farmers, extension workers, and government officials often lack the skills and knowledge needed to effectively leverage digital tools for risk management.

The challenge of ensuring equitable access emerges as a critical concern, with women farmers facing particular barriers due to sociocultural constraints, limited device access, lower digital literacy rates and exclusion from formal financial systems. Indigenous communities and ethnic minorities often find that digital solutions fail to accommodate their languages, cultural practices and traditional knowledge systems. The elderly and youth face different but equally significant challenges in accessing and benefiting from digital agricultural services, highlighting the importance of targeted approaches that address diverse user needs and capabilities.

Governance challenges associated with digital transformation raise fundamental questions about data ownership, privacy, algorithmic accountability and technological sovereignty. As digital platforms collect vast amounts of data about farming practices, land use and market transactions, concerns grow about how this data is used, who benefits from its value and what rights farmers have over their own information.

The experiences documented throughout this analysis point to several critical insights for moving forward. First, technology alone cannot transform disaster risk management without corresponding investments in human capacity, institutional development and an enabling infrastructure. The most successful digital interventions combine technological innovation with sustained capacity building, participatory design processes and integration into existing institutional frameworks.

Second, comprehensive approaches that address multiple dimensions of risk and vulnerability prove more effective than narrow, technology-focused interventions. Digital early-warning systems achieve greater impact when linked to anticipatory financing mechanisms, community preparedness programmes and social protection systems. Third, context-specific solutions are essential, as digital tools succeeding in one context may fail in another due to differences in infrastructure, institutional capacity, cultural factors or risk profiles. Finally, the critical role of partnerships and collaboration becomes evident, requiring new forms of cooperation that transcend traditional sectoral boundaries.

Building on these insights, several priority areas emerge for transformative action. The development of integrated assessment frameworks that capture the full spectrum of disaster impacts represents a fundamental requirement for evidence-based risk management. These frameworks must expand beyond economic metrics to systematically assess nutritional impacts, ecosystem service disruptions, cultural heritage losses and differential social effects, while adopting longitudinal approaches that track impacts over multiple years. Bridging the digital divide through innovation emerges as perhaps the most critical challenge, requiring comprehensive strategies that address not only technical infrastructure but also human capacity, affordability and cultural appropriateness.

Strengthening data governance and interoperability represents another critical priority, with robust frameworks needed to balance protecting farmers' rights and privacy with enabling innovation and data sharing for collective benefit. National data governance frameworks should clarify ownership, access rights and usage permissions, while establishing accountability mechanisms for algorithmic decision-making systems. The integration of digital solutions into national strategies and institutional frameworks represents a crucial step for moving beyond pilot projects to achieve systemic transformation at scale.

The financial requirements for comprehensive digital transformation and resilience-building, while substantial, remain achievable within the context of current disaster losses and development financing. The USD 3.26 trillion in agricultural losses over three decades far exceeds the investments needed for building resilient agrifood systems, with evidence consistently showing positive returns on investment in disaster risk reduction. The question is not whether resources are available but how to mobilize and direct them effectively towards transformative solutions that address root causes rather than symptoms.

International cooperation plays a crucial role in this transformation, with multilateral organizations providing technical leadership while ensuring solutions reflect local ownership and priorities. The private sector brings essential innovation and resources, but must be engaged in ways that ensure equitable access and benefit sharing. Civil society organizations play vital roles in advocating for participatory solutions and ensuring accountability, while their deep connections with farming communities make them essential partners in designing and implementing digital solutions that truly serve user needs.

Most fundamentally, farming communities themselves must be recognized and empowered as primary agents of change rather than passive beneficiaries of external interventions. Their knowledge, priorities and innovations must shape digital transformation, rather than having solutions imposed upon them. Building truly resilient agrifood systems requires combining wisdom accumulated through generations of farming experience with possibilities enabled by digital innovation in ways that respect both tradition and transformation.

As we stand at this critical juncture, the choices made today will determine the resilience and sustainability of global agrifood systems for generations to come. The digital revolution offers powerful tools for transformation, but tools alone do not create change. Change requires visionary policies prioritizing resilience and sustainability, institutional commitment sustaining efforts beyond political cycles, and multistakeholder engagement bringing together diverse perspectives and capabilities.

INDIA
Farmer carrying sacks on his head during rainy season.
© iStock/pixelfusion3d

PART 1

INTRODUCTION

AGRICULTURE AT THE CROSSROADS OF CRISIS AND INNOVATION

The past two years have witnessed an unprecedented convergence of disasters that have profoundly impacted global agriculture, underscoring both the vulnerability of food production to multiple hazards and the urgent need for transformative approaches to disaster risk reduction. From devastating droughts that have gripped entire continents to catastrophic floods that have swept away decades of agricultural development, from transboundary pest outbreaks that have threatened food security across regions to conflicts that have disrupted global food supply chains, the agricultural sector has faced a relentless succession of shocks that have tested the limits of existing risk management approaches.

The year 2023 began with the continuation of a severe multiyear drought across the Horn of Africa, affecting over 36 million people and decimating livestock herds that represent the primary source of livelihoods for pastoral communities. In Somalia, Ethiopia and Kenya, consecutive failed rainy seasons led to the death of over 13 million livestock, destroying the economic foundation of millions of households and pushing communities to the brink of famine.[1] The impact of the drought extended beyond immediate livestock mortality to disrupt entire pastoral systems, as traditional migration routes became untenable, water sources dried up and rangeland degradation accelerated beyond the recovery capacity of natural systems.

Simultaneously, South America experienced one of its worst droughts in recent history, with the Amazon basin recording its lowest water levels in over a century. The drought devastated crop production across Brazil, Argentina and Uruguay, with soybean and corn yields falling by up to 40 percent in some regions.[2] The effects rippled through global commodity markets, contributing to food price inflation and affecting food security far beyond the directly impacted areas. The drought also exacerbated forest fire risks, with millions of hectares of forest and agricultural land burning across the continent, releasing massive amounts of carbon and destroying the biodiversity that underpins agricultural sustainability.

Contrasting with these drought emergencies, 2023 also witnessed devastating floods across multiple regions. In Pakistan, monsoon floods affected over 9 million people and destroyed 849 000 hectares of crops, coming just one year after the catastrophic 2022 floods from which the country was still recovering.[3] The consecutive flooding events have fundamentally altered Pakistan's agricultural landscape, with soil erosion, salinization and infrastructure destruction creating long-term challenges for agricultural recovery. In Libya, Storm Daniel caused catastrophic flooding that not only resulted in thousands of deaths but also destroyed agricultural infrastructure and contaminated productive lands with debris and pollutants that will affect farming for years to come.[4]

The El Niño phenomenon that emerged in mid-2023 brought additional challenges to global agriculture, disrupting weather patterns across the Pacific, Indian and Atlantic basins. In Southern Africa, El Niño-induced drought affected over 20 million people across Zimbabwe, Zambia and Malawi, with maize production falling by up to 70 percent in some areas.[5] The reduced harvests forced countries to declare states of disaster and appeal for international assistance to prevent widespread hunger. Meanwhile, El Niño brought excessive rainfall to East Africa, causing flooding that destroyed crops and infrastructure in areas still recovering from consecutive years of drought, demonstrating the growing volatility and extremes increasingly characterizing climate-affected agrifood systems.

The year 2024 has continued this pattern of devastating disasters in agriculture. Tropical Storm Filipo came just one year after Cyclone Freddy – the longest-lasting tropical cyclone on record – traversed the Indian Ocean for over five weeks and ravaged several parts of Madagascar, Mozambique and Malawi. The continuous cycle of disaster losses continued after the cyclone had already destroyed over 1.2 million hectares of crops, with smallholder farmers losing not only their current harvest but also their seed stocks for future planting seasons.[6] The storm's unprecedented duration and intensity overwhelmed coping mechanisms, as communities that might normally recover from a single cyclone impact found themselves facing repeated battering that depleted their resilience.

Biological hazards have added another layer of complexity to the disaster landscape. The continuing spread of ASF across Asia and into new regions has devastated pig populations, with Viet Nam, the Philippines and China reporting millions of culled animals.[7] The impact of the disease extends beyond direct livestock losses to disrupt entire value chains, affect feed crop demand and alter global protein markets. Similarly, the fall armyworm (FAW) continues its relentless spread, with new invasions reported in previously unaffected regions and evolved resistance to control measures posing challenges to management strategies in areas where the pest has become established.

The locust situation, while improved from the 2019–2021 crisis, remains precarious, with favourable breeding conditions in traditional recession areas threatening new upsurges.[8] Countries across the Sahel, Arabian Peninsula and Southwest Asia maintain vigilant surveillance, knowing that a failure to detect and control initial populations could lead to another devastating regional outbreak. The resources required for this continuous surveillance strain national budgets, which are already stretched by multiple concurrent disasters.

Forest fires have emerged as an increasingly severe threat to agriculture, with 2024 and 2025 witnessing record-breaking fire seasons across multiple continents. In Canada, 3.24 million hectares had already burned by June 2025. This is only rivalled by the record-breaking 18 million hectares that burned in 2023, with smoke plumes affecting air quality and agricultural productivity even thousands of kilometres away.[9] The fires destroyed timber resources, affected wildlife populations that provide ecosystem services to agriculture and created long-term soil degradation in burned areas. In the Mediterranean region, intense heat waves combined with drought conditions create explosive fire conditions that destroy olive groves, vineyards and other agricultural lands that have been cultivated for centuries.[10]

The fisheries and aquaculture sectors have faced their own set of catastrophic challenges. Marine heatwaves have become more frequent and intense, with the Mediterranean Sea experiencing its highest recorded temperatures in 2024.[11] These thermal anomalies have disrupted fish populations, caused mass mortality events in aquaculture facilities, and altered the distribution of species in ways that affect both commercial and subsistence fishing communities. In Peru, the warming associated with El Niño caused a 50 percent reduction in anchoveta catches, the world's largest single-species fishery, affecting global fishmeal supplies and the aquaculture industry that depends on them.[12]

Conflicts and geopolitical tensions have added another dimension to how disasters affect agriculture. The ongoing conflict in the Sudan has displaced millions of farmers during critical planting seasons, destroyed irrigation infrastructure, and disrupted seed and fertilizer supply chains. The compounding effects of conflict and climate extremes have created conditions where existing coping mechanisms are failing, and humanitarian assistance is struggling to reach affected populations. Similarly, conflicts in the Sahel region have prevented farmers from accessing their fields, disrupted transhumance routes for pastoralists and created conditions where agricultural production collapses even in areas with favourable weather conditions.[13]

The cumulative impact of these disasters over the past two years has exposed fundamental vulnerabilities in global agrifood systems, while highlighting the inadequacy of current approaches to disaster risk management. The increasing frequency, intensity, and complexity of disasters is overwhelming response capacities that were originally designed for less severe and less frequent events. The simultaneous occurrence of multiple hazards creates compound impacts that exceed the sum of individual effects, while the rapid succession of disasters prevents recovery between events, leading to a progressive erosion of resilience.

Yet alongside these mounting challenges, the past two years have also witnessed remarkable advances in digital technologies that offer new possibilities for understanding, predicting, and managing disaster risks and impacts in agriculture and agrifood systems. The proliferation of satellite technology with new constellations that provide daily high-resolution imagery of the globe has transformed our ability to monitor agricultural conditions in near-real time. AI and ML algorithms can now process vast amounts of data to detect subtle patterns that indicate emerging risks – from early signs of pest outbreaks to predictions of yield impacts from weather anomalies.

The expansion of mobile network coverage and the declining cost of smart devices have brought digital connectivity to previously isolated rural communities, opening new channels for delivering information, services and support to farmers. Digital platforms that combine weather forecasts, agronomic advice, market information and financial services are empowering farmers with tools that were unimaginable just a decade ago. Despite the devastating impacts of the COVID-19 pandemic, it accelerated digital adoption and demonstrated the potential for remote sensing, digital payments and virtual extension services to maintain agricultural support even when physical movement is restricted.

Innovations in financial technology have made crop insurance accessible to millions of smallholder farmers through parametric products that use satellite data and weather indices to trigger automatic payouts. Blockchain technology promises to enhance supply chain transparency and enable new forms of collective action for risk management. IoT sensors deployed in fields, storage facilities, and transportation systems generate continuous streams of data that enable precision management and early problem detection. Drone technology has moved from experimental to operational use, providing affordable high-resolution monitoring and even direct intervention capabilities for pest control and input application.

However, the potential of these technological advances remains largely unrealized due to persistent challenges in the implementation, adoption and integration into existing systems. The digital divide continues to exclude many of the most vulnerable agricultural communities from accessing these innovations. Questions of data ownership, privacy and control raise concerns about whether digital transformation will empower farmers or create new forms of dependency. The fragmentation of digital initiatives and lack of interoperability between platforms limit their collective impact, while the focus on technological solutions sometimes obscures the need to address underlying structural vulnerabilities.

This report addresses these critical challenges by providing a comprehensive analysis of disaster impacts on agriculture and the role of digital innovations in transforming disaster risk management. **Part 2** offers a systematic examination of how disasters affect agriculture, moving beyond production losses to explore the complex pathways through which impacts cascade through infrastructure, markets, financial systems and ecosystem services. It highlights the importance of considering non-economic impacts, vulnerabilities of men and women, differentiated ecosystem effects, and long-term consequences that are difficult to measure but may be equally or more important for understanding total disaster impacts.

The analysis in **Part 2** demonstrates that disaster impacts in agrifood systems extend far beyond the immediate and visible destruction of crops and livestock. Disasters disrupt the intricate web of relationships that sustain agriculture, from the soil microbiomes that maintain fertility to the social networks that enable collective action for risk management. The examination of slow-onset disasters reveals how gradual changes can cause greater cumulative damage than sudden events, yet often fall below the threshold for triggering response mechanisms. The exploration of climate as a risk amplifier shows how shifting baselines and increasing variability create new patterns of risk that challenge traditional knowledge and management systems.

The examination of current monitoring tools – including the Sendai Framework Monitor and Post-Disaster Needs Assessments – reveals both their value in standardizing impact measurement and their limitations in capturing the full spectrum of disaster consequences. The analysis shows how data gaps, reporting inconsistencies, and methodological constraints create an incomplete picture that can misguide policy and investment decisions.

Hazard types considered in Part 2

- **HYDROMETEOROLOGICAL:**
  Flood, drought, cyclone, storms, extreme temperatures, marine heatwave
- **GEOPHYSICAL:**
  Earthquake, volcanic activity, tsunami, landslide
- **BIOLOGICAL:**
  Plant and animal pest and disease, Insect infestation
- **ENVIRONMENTAL:**
  Wildfire and forest fire

Finally, **Part 2** also provides a quantitative assessment of global losses in crop and livestock production, utilizing counterfactual methodologies that combine production data with disaster event records to estimate impacts across 191 agricultural commodities in over 200 countries and territories. The results reveal not only the staggering scale of losses – over USD 3.26 trillion over 33 years – but also important patterns in how disasters affect different regions, income groups and agricultural subsectors. The nutritional analysis adds a crucial dimension by showing how production losses translate into losses of essential nutrients, with implications for public health and human development that extend beyond economic metrics. The special attention to fisheries and aquaculture highlights how entire subsectors remain largely invisible in disaster assessments, despite their crucial importance for food security and livelihoods.

Part 3 pivots from analysing conceptual gaps and agricultural losses to exploring solutions, providing a comprehensive examination of how digital technologies are transforming disaster risk management in the agriculture sector. It begins by establishing the landscape of digital innovations, from remote sensing and AI to mobile applications and blockchain, showing how these technologies address specific challenges in risk assessment, early warning, response and recovery. The analysis moves beyond technical capabilities to examine implementation experiences, revealing both successes and failures that provide crucial lessons for scaling digital solutions.

The exploration of digital tools for risk knowledge and monitoring demonstrates how advances in data collection, processing and visualization are revolutionizing how we understand agricultural risks. Platforms that integrate climate data, soil information, pest and disease surveillance, and market intelligence provide decision-makers with unprecedented capabilities for evidence-based planning and response. The examination of digital advisory services shows how mobile technologies are democratizing access to agricultural knowledge, while delivering personalized recommendations that help farmers optimize production while managing risks.

Part 3 provides a detailed analysis of how digital innovations enable the shift from reactive response to proactive prevention and anticipatory action. Early-warning systems that combine multiple data sources with sophisticated predictive models can now provide alerts weeks or even months before disasters strike, creating windows of opportunity for proactive disaster risk reduction action. Integrating early warning with pre-arranged finance and pre-agreed anticipatory action protocols demonstrates how technology can catalyse systemic changes in disaster risk management. Case studies from Somalia, Rwanda, the Sudan, and other countries illustrate both the potential and the challenges of implementing these approaches at scale.

The examination of digital financial services reveals how technology is revolutionizing risk transfer and social protection in agriculture. Mobile money platforms enable rapid delivery of assistance to disaster-affected populations, while parametric insurance products make crop insurance accessible to farmers previously excluded from existing indemnity-based systems. The analysis shows how bundling insurance with advisory services and input provision creates synergies that enhance both risk protection and productivity improvement.

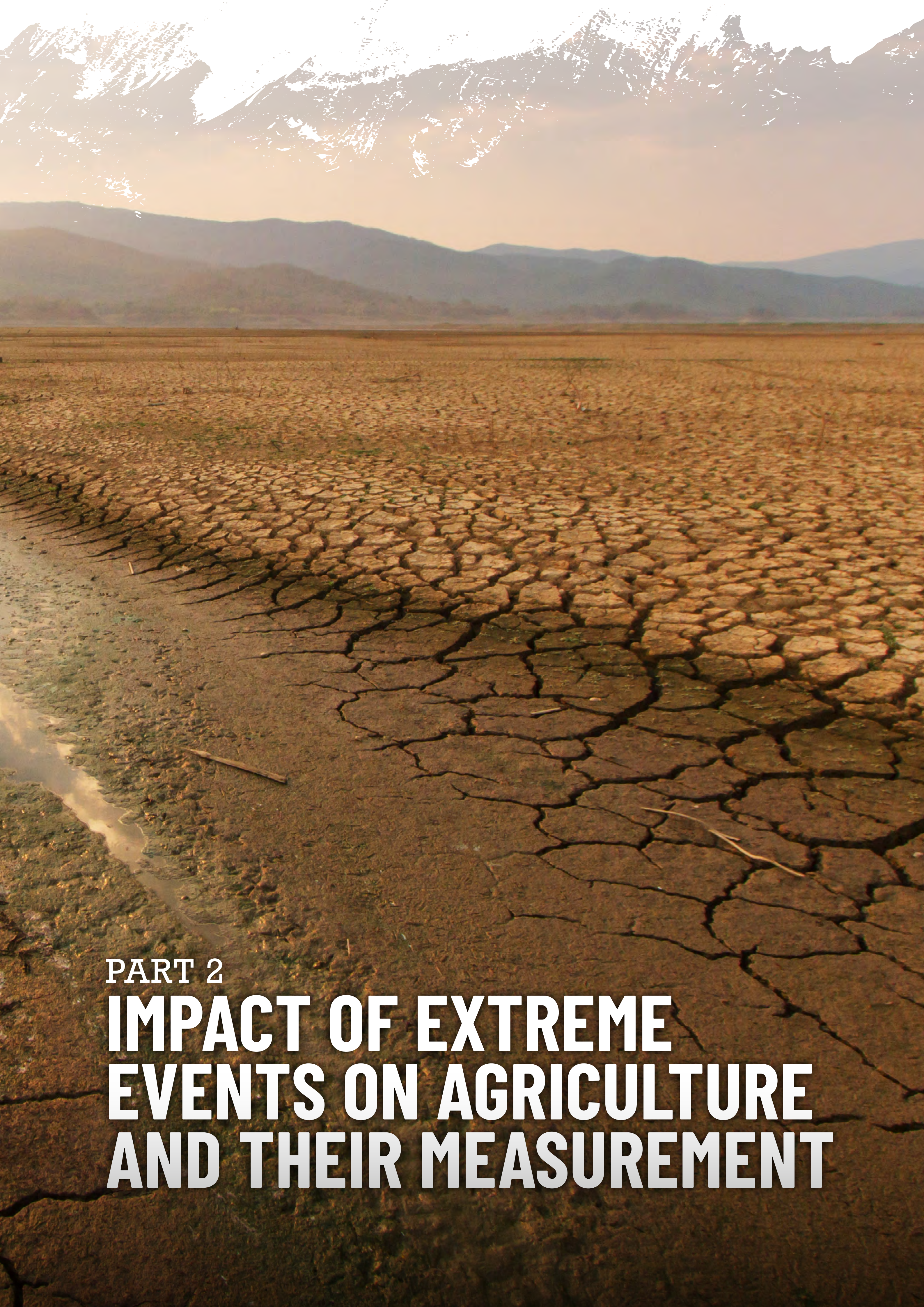
Part 3 concludes by examining the enabling conditions necessary for successful digital transformation in agricultural disaster risk management. It explores requirements for digital infrastructure, data governance frameworks, institutional coordination mechanisms and human capacity development. The analysis of implementation pathways draws lessons from country experiences to identify success factors and common pitfalls. The emphasis on human-centred design principles highlights how technological solutions must be grounded in understanding user needs, capabilities, and contexts to achieve sustainable adoption and impact.

The synthesis of findings from **Parts 2** and **3** reveals a fundamental insight: understanding the full complexity of disaster impacts is a prerequisite to developing effective solutions, while digital innovations provide unprecedented capabilities for both assessment and response. The report demonstrates that the transformation of agricultural disaster risk management requires not just technological innovation, but systemic changes in how we conceptualize, measure and respond to agricultural risks. It shows that digital solutions achieve the greatest impact when they address the gaps and limitations identified through comprehensive impact assessment, creating a virtuous cycle where a better understanding enables better response, ultimately generating better data for continuous improvement.

This report comes at a critical moment when the convergence of escalating disaster risks and transformative digital capabilities is creating both urgency and opportunity for fundamental change. The window for building agrifood systems capable of feeding a growing global population while adapting to climate shocks is narrowing rapidly. Yet the tools, knowledge, and examples of success documented in this report demonstrate that transformation is possible when vision aligns with action and resources match ambition. By providing a comprehensive analysis of both challenges and solutions, this report aims to inform and inspire the collective action necessary to build resilient agrifood systems that can thrive despite mounting disaster risks.

The journey toward agricultural resilience in an era of mounting disasters is complex and demanding, but it is a necessity, not a choice. The lives and livelihoods of billions depend on our collective ability to transform how we understand and manage agricultural risks. This report provides a roadmap for that transformation, grounded in evidence, inspired by innovation, and focused on the ultimate goal of ensuring food security, prosperity and achieving better nutrition for all. The time for incremental adjustments has passed; what is needed now is transformative action that matches the scale and urgency of the challenge. Through the systematic analysis of disaster impacts and the strategic deployment of digital innovations that shape resilience solutions and interventions on the ground, we can build agrifood systems that not only survive but thrive in an uncertain future. ■

THAILAND
Dry lake and riverin summer – impact of drought.
© iStock/piyaset



PART 2

IMPACT OF EXTREME EVENTS ON AGRICULTURE AND THEIR MEASUREMENT

KEY MESSAGES

→ **Disasters have inflicted an estimated USD 3.26 trillion in agricultural losses over 33 years (1991–2023)**, averaging at USD 99 billion per year, with cereal crops bearing the heaviest burden at 4.6 billion tonnes lost, followed by fruits and vegetables (2.8 billion tonnes), and with meat and dairy losing 900 million tonnes.

→ **At the regional level, Africa is estimated to bear the highest relative burden at 7.4 percent of agricultural GDP** despite lower absolute losses. **Lower-middle-income countries face the highest relative agricultural losses at 5 percent of agricultural GDP**, exceeding both low-income countries (3 percent) and high-income countries (4 percent), revealing a critical gap where high exposure and vulnerability combine with limited resilient infrastructure.

→ **Losses in production resulting from disasters correspond to a reduced availability of 320 kcal per person per day globally**, with iron losses corresponding to 60 percent of requirements for men and critical shortfalls in essential vitamins and minerals that have the potential to disproportionately affect vulnerable populations.

→ **Marine heatwaves alone are estimated to have caused USD 6.6 billion in fisheries losses (1985-2022)**, with 15 percent of global fisheries affected and production losses exceeding 5.6 million tonnes, demonstrating the severe yet largely unmeasured impacts on aquatic food systems. Still, fisheries and aquaculture remain largely invisible in disaster assessments, despite providing livelihoods for 500 million people.

→ **Disaster impacts on agriculture extend far beyond immediate production losses** to include infrastructure damage, market disruptions, financial system failures and ecosystem service degradation that can persist for years after initial events. Current assessment tools must be extended to systematically capture both direct and indirect impacts and take into consideration non-economic values, differentiated effects on vulnerable groups, biodiversity losses and long-term ecosystem disruptions.

The agricultural sector faces unprecedented challenges from increasingly frequent and severe disasters that are fundamentally reshaping how we approach impact assessment and measurement in agrifood systems. The economic ripple effects of disasters extend far beyond immediate production losses, as demonstrated by recent major events. For instance, the 2018 drought in Europe caused agricultural losses exceeding EUR 9 billion,[14] while the 2019–2020 Australian bushfires resulted in agricultural losses of over AUD 5 billion, destroying livestock, crops, wildlife and agricultural infrastructure across vast areas.[15] The 2021 extreme heat dome in North America resulted in agricultural losses exceeding USD 600 million in the Pacific Northwest alone, devastating fruit crops and causing widespread livestock mortality that affected regional food supplies for several months.[16]

These examples illustrate how localized disasters can have cascading and transboundary impacts on global agrifood systems, affecting prices, trade patterns and food security far beyond the initial impact zone. The interconnected nature of modern agrifood systems means that disruptions in one region can quickly propagate through international markets, supply chains and trade relationships, creating vulnerabilities that extend well beyond the immediately affected areas. Understanding these complex impact pathways is essential for developing effective assessment methodologies and response strategies that address both local and systemic consequences of disasters for the agricultural sectors.

Although the foundation of effective disaster risk reduction lies in improving risk knowledge and the accurate measurement and comprehensive understanding of how disasters disrupt agrifood systems, the systematic documentation and analysis of these impacts is limited by methodological and practical constraints. Current assessment approaches are limited to evaluating immediate production losses and economic costs. They are unable to systematically capture the complex, cascading effects that ripple through interconnected agrifood systems, resulting in an underestimation of disaster consequences and inadequate evidence for informed recovery and resilience building.

As a first step towards accounting for both immediate, direct losses and the longer-term, indirect impacts of disasters on agrifood systems, the first chapter of this part of the report outlines the main trajectories and dimensions through which such extreme events disrupt agricultural production, value chains and livelihoods. Only through the identification of appropriate loss components and variables – *what, exactly, is being lost?* - can we develop analytical frameworks to capture the full complexity of disaster impacts on agriculture.

This is followed by a review of the two main tools that monitor the global impacts of disaster events and provide a breakdown of losses for the agricultural sector – namely the Sendai Framework Monitor and the PDNAs. Updated data from these two sources are analysed to demonstrate the relative share of losses in agriculture versus other productive sectors, and impacts in agriculture by hazard types.

The last chapter presents estimates of global losses in crop and livestock production, utilizing a methodology developed by the Statistics Division at FAO and drawing on production data for 191 agricultural commodities across 205 countries and territories from FAOSTAT, as well as disaster event data from EM-DAT.[17] The model offers insights into the overall loss trends in agriculture and reveals variable levels of vulnerability and risk experienced in agricultural sectors across regions, subregions and country income groups. In the absence of systematic data to analyse production losses in the fisheries subsector, a limited evaluation of the impact of marine heatwaves on fisheries is presented as a first step towards more comprehensive assessments in the future. ■

2.1 THE COMPLEX NATURE OF DISASTER IMPACTS ON AGRICULTURE

Today's agricultural systems face escalating pressures from disasters that extend beyond immediate production losses to encompass complex disruptions across entire agrifood value chains. The interconnected nature of modern agrifood systems means that a disaster affecting one component can trigger cascading effects through multiple pathways, often resulting in impacts greater than the sum of its parts.

The vulnerability of agricultural systems is also compounded by their exposure to multiple, often simultaneous hazards that create complex emergencies, which ultimately challenge established risk management approaches. In 2020, East Africa faced a "triple threat" of the COVID-19 pandemic, flooding and desert locusts, creating a complex emergency that reactive disaster management practices struggled to address.[18] The compounding effects of these simultaneous crises led to a 20 percent increase in acute food insecurity in the region.[19] Similarly, Cyclone Idai, which struck Southern Africa in 2019, did not just destroy 780 000 hectares of crops on impact, but it also triggered cholera outbreaks and created conditions for increased pest infestations, affecting 3 million people across Mozambique, Zimbabwe and Malawi.[20] The interaction between these different types of crises created synergistic effects that exceeded what any single hazard might have produced, highlighting the need for integrated assessment approaches that can capture compound and cascading risks.

The temporal dimension of impacts presents unique challenges for loss assessments, as effects may emerge immediately during disaster events but also develop gradually over months or years as recovery processes unfold and secondary impacts become apparent. Similarly, spatial complexity adds another layer of difficulty, as the impact of disasters on agriculture often extends far beyond the immediate disaster zone through market linkages, supply chain disruptions and population movements.

These examples underscore the fundamental challenge facing assessments of disaster impacts in agriculture: understanding these multifaceted impacts requires comprehensive frameworks that capture the full spectrum of consequences across temporal, spatial and sectoral dimensions. The following section systematically outlines how disasters can impact agricultural systems, laying the groundwork for developing methodologies and indicators that capture the complex, interconnected nature of contemporary disaster risks.

PATHWAYS OF AGRICULTURAL SYSTEM DISRUPTION

Understanding the transmission pathways and mechanisms of agricultural losses is essential for developing comprehensive impact assessment frameworks that can capture the full scope of disaster impacts and inform effective response and recovery strategies (see TABLE 1). The most visible and immediate pathway through which disasters affect agriculture occurs through disruptions to production systems themselves. Yet even these straightforward impacts involve complex interactions between environmental stresses, biological systems and management practices. Extreme weather events destroy crops through multiple mechanisms, including physical damage from hail, wind and flooding, as well as physiological stress from temperature extremes and moisture deficits. These primary impacts often trigger secondary effects such as increased pest and disease pressure in weakened plants, creating cascading consequences that extend beyond the initial damage.[21] For instance, increased humidity resulting from flooding can create favourable conditions for fungal pathogens, while stressed plants may exhibit compromised immune responses.[22] Livestock systems experience similar multifaceted impacts, including direct mortality from extreme weather, heat stress »

TABLE 1

PATHWAYS OF DISASTER IMPACTS IN AGRICULTURE

DIMENSIONS OF IMPACTS	IMMEDIATE IMPACTS	MEDIUM-TERM TO LONG-TERM EFFECTS	
Production	Destroyed stocks Production losses	Disease and pest pressures Reduced productivity Reduced reproductive performance Physiological stress	Reduced yields Reduced product quality Reduced nutrient availability Reduced productivity
Infrastructure	Damaged equipment Damaged processing facilities Disrupted irrigation/water supply Damaged storage facilities Damaged transport facilities (roads, ports) Disrupted energy supply Disrupted communication networks/early-warning systems	Site contamination Processing delays Spoilage losses from cold chain/ other disruptions Increased transportation costs Restricted transportation corridors Transport delays Reduced food safety and quality	Infrastructure irrelevance/ breakdown Increased transportation costs Increased energy costs
Financial	Access to banking and insurance Price shocks and volatility Access to credit markets	Depressed farm-gate prices Market access constraints (credit) Higher insurance premiums/ access	–
Inputs	Supply chain disruptions Procurement of seeds, feed, fertilizers, pesticides and equipment	Reduced availability/access to inputs Increased input prices	–
Outputs	Disrupted market linkages and facilities	Delivery schedules not met Volume/consistency standards for export markets Reduced market share/exports	–
Human/social	Reduced income Reduced employment Lower labour capacity Health impacts and disease outbreaks	Lower purchasing power for nutritious food Migration and demographic changes Reduced economic opportunities, especially for women Increased burden of care	Declining food security and access Loss of traditional agricultural knowledge and practices Cultural landscapes and livelihoods
Environmental	Water availability Soil quality Habitat destruction and biodiversity loss	Fish stock migration Pollution and run-off	Water stress/depleted groundwater resources Soil degradation/desertification Pasture quality Disrupted seasonal/crop cycles Pest and disease infestations
Management/ governance	Increased expenditures on recovery	Trade policies	Reduced tax revenues Lower GDP

Source: Authors' own elaboration.

» that reduces productivity and reproductive performance, disrupted feed supplies that compromise animal nutrition and disease outbreaks that can spread rapidly through stressed populations.[23]

Adding another layer of complexity to impact assessment, the temporal dynamics of these disruptions vary significantly. While some effects are felt immediately – such as crop destruction from severe storms – others develop gradually, including the weakening of plants from prolonged stress, reduced long-term productivity due to soil degradation and diminished future production capacity from the loss of breeding stock. Perennial crops such as fruit trees and coffee present unique assessment challenges, as damage may not become fully apparent until subsequent growing seasons, while recovery may require multiple years of replanting and establishment before productive capacity is restored.[24,25]

The intersection between production impacts and environmental degradation becomes particularly evident in fisheries and aquaculture systems. Disasters can simultaneously affect fish stocks through direct mortality, habitat destruction and water quality deterioration. Coastal aquaculture facilities are particularly vulnerable to storm surge, saltwater intrusion and infrastructure damage, while inland systems may be affected by flooding, drought or pollution from agricultural runoff.[26] The mobile nature of wild fish populations introduces an additional challenge, as environmental changes can cause stock migrations that affect fishing communities far from the original disaster area.

Beyond direct production impacts, the destruction and damage of infrastructure create bottlenecks that amplify and extend the effects of disasters throughout agrifood systems, often resulting in consequences that persist long after production systems have recovered.[27,28] When transportation networks experience disruption, farming communities become isolated from input suppliers and output markets, creating both immediate access problems and longer-term economic consequences. In Nepal, farmers struggled to obtain necessary inputs for the next growing season or market their products post-harvest after the 2015 earthquake.[29] The strategic importance of specific infrastructure elements means that damage to key facilities such as ports, processing plants or major transportation corridors can reverberate throughout entire regional agrifood systems.

Storage and processing facilities emerge as critical vulnerability points throughout the production and agrifood system. Damage to these facilities can result in massive food losses even when primary production remains intact. Cold storage facilities are particularly vulnerable to power outages, which can render high-value perishable products unusable within hours.[30] Grain storage facilities may experience moisture intrusion, pest infestation or structural damage that render stored products unmarketable.[31] When processing plants experience equipment damage, contamination or operational disruptions, their impaired capacity to handle agricultural products creates bottlenecks that can lead to production losses, even in areas with undamaged farming operations.[32]

These infrastructure impacts become compounded when communication systems fail, limiting farmers' access to critical information about weather conditions, market prices, input availability and technical assistance.[33] The increasing reliance on digital technologies for farm management, market access and government services means that communication disruptions can simultaneously affect multiple aspects of agricultural operations. Early-warning systems become ineffective when communication networks are damaged, limiting the ability of farmers to take protective actions before subsequent disaster events and thereby increasing their vulnerability to cascading impacts.

Similarly, widespread effects occur when energy infrastructure sustains damage, affecting irrigation systems, cold storage facilities, processing operations and transportation networks. These impacts cascade throughout the agrifood system in complex ways.[34] Irrigation system failures can lead to crop losses even when water supplies remain adequate, while processing plant shutdowns create bottlenecks that affect multiple farming operations simultaneously. The interconnected nature of energy systems means that damage to generation, transmission, or distribution infrastructure can impact agricultural operations across broad geographic areas, resulting in regional-scale disruptions from localized damage.[35]

The financial dimension of disaster impacts creates additional layers of disruption by limiting access to credit, insurance, and other essential financial services necessary for agricultural operations and recovery. Banking systems may experience physical damage or operational disruptions that limit the ability of farmers to access funds for inputs, equipment repair, or household needs during critical periods for planting or harvesting. The concentration of financial services in urban areas means that rural agricultural communities often face prolonged periods without access to banking services following disasters that damage transportation or communication infrastructure, creating hardships for remote farming operations. A study of the 2019 floods in the Islamic Republic of Iran found that rural communities with access to a local bank branch experienced early recovery due to immediate access to financial services, although the banking facilities themselves faced higher physical risks due to their greater exposure to hazards.[36]

In the aftermath of major disasters, insurance systems frequently become overwhelmed by claims, potentially restricting coverage for future seasons and creating additional uncertainty for agricultural producers as they attempt to plan recovery investments. The interdependence between insurance markets and capital markets means that major disasters can affect insurance availability and pricing across entire regions or sectors, influencing risk management decisions for farmers who were not directly affected by the initial disaster.[37] This ripple effect through insurance markets can fundamentally alter the risk landscape for agricultural production across broad geographic areas.

As disaster impacts move through financial systems, credit markets typically tighten as lenders become more risk-averse, constraining capital availability for both immediate recovery and longer-term adaptation investments. As was the case after Hurricane Katrina, such credit constraints affected not only farmers directly impacted by the disaster but also those in surrounding areas or similar production systems, as lenders reassessed risk profiles across entire sectors or regions.[38] The timing of credit restrictions relative to agricultural production cycles proves particularly problematic when farmers struggle to access necessary financing during critical planting periods, potentially affecting multiple growing seasons.

The economic consequences of disasters extend further through disruptions to market access, affecting both input procurement and output marketing. These disruptions create economic impacts that may persist long after physical infrastructure is repaired and can fundamentally affect the viability of farming operations even when production capacity is restored. Input suppliers experiencing supply chain disruptions increase costs and reduce the availability of seeds, fertilizers pesticides and equipment.[39] Farmers in remote areas who depend on complex supply chains for essential inputs face unique vulnerabilities. Indeed, these disruptions can affect multiple growing seasons if farmers are unable to obtain quality seeds or other essential inputs during critical planting periods, resulting in long-term impacts on productivity.

On the output side, markets become disrupted through multiple pathways, including damaged transportation infrastructure, reduced storage capacity, destroyed processing facilities and consumer concerns about food safety from disaster-affected areas. The perishable nature of many agricultural products means that even temporary market access problems can result in total product losses. Longer-term market disruptions impact farmer income and investment decisions, shaping agricultural development trajectories for years to come. Price volatility increases as supply disruptions interact with speculative trading, hoarding behaviour, and emergency purchasing by governments and humanitarian organizations, creating uncertainty that affects planning decisions throughout agrifood systems.[40]

These local and regional impacts ultimately connect to global systems through international trade, demonstrating how disasters in one location can have far-reaching consequences through interconnected markets.[41] As seen during the spread of ASF in China's pork industry in 2018 and 2019, when major producing regions experience disasters that affect global supply chains and commodity prices, the effects ripple through international markets.[42] Export disruptions can affect foreign exchange earnings and market reputation for entire countries, while import dependencies make countries vulnerable to disasters occurring in their main supplier regions. Trade policy responses to disasters, such as export restrictions or emergency imports, can further exacerbate market disruptions and impact global food security, creating feedback loops that extend and intensify the original disaster's impacts across international boundaries.

A comprehensive understanding of disaster impacts requires recognizing that agricultural systems generate both economic outputs that can be quantified in monetary terms and non-economic values that are harder to quantify but may be equally or more valuable for community welfare, cultural identity and long-term sustainability. This distinction is crucial for developing assessment methodologies that capture the full range of disaster impacts and inform response strategies that address all dimensions of impact rather than focusing solely on measurable economic losses.

The economic dimension of disaster impacts on agriculture – some of which were outlined in the previous section – includes damage and loss that can be valued using market prices or established economic methodologies, providing quantifiable measures that enable comparison across different hazard types, regions and time periods. Among these, physical asset damage – including destroyed or damaged crops, livestock mortality, damaged equipment and buildings, and infrastructure destruction – can be valued using replacement costs, market values or depreciated replacement costs, depending on the specific assets involved. As mentioned in the previous section, this direct physical damage is often the most visible and immediately apparent consequence of disasters, making it an expected primary focus for initial assessment efforts.

Beyond the immediate destruction of physical assets, disasters generate production losses that represent foregone output, which can be quantified using yield data, production statistics and market prices to estimate the monetary value of lost agricultural production (see **Section 2.3**). These losses may result from complete crop failure, reduced yields due to stress or damage, or disrupted production cycles that affect the timing and quality of output. Estimating livestock production losses can be more complicated as it includes not only direct mortality but also reduced productivity resulting from stress, disrupted breeding cycles and compromised animal health, which may persist for extended periods following the initial disaster event.

The measurement of the human dimensions of the economic impact of disasters requires a broader scope of assessment. It must also examine how loss of income affects anyone whose livelihood depends on agriculture, including farmers and agricultural workers, and the ripple effects of disasters throughout rural economies that often extend beyond the agricultural sector itself.[43,44] This loss of income may result from reduced production, lower product prices, increased input costs or lost employment opportunities in agriculture-dependent communities. The distribution of income losses across different population groups reflects existing structural inequalities and vulnerabilities, with smallholder farmers, agricultural workers, women and other marginalized groups often experiencing disproportionate impacts.[45]

As disasters reverberate along agricultural value chains, they generate economic losses that impact processing, storage, transportation and marketing activities throughout the agrifood system. Disruptions in interconnected value chains can lead to indirect impacts such as increased transportation costs, spoilage losses from broken cold chains, processing delays that reduce product quality, diminished processing capacity and market access constraints that depress farm-gate prices. These impacts are amplified in international markets when disaster-affected regions are unable to meet delivery schedules or maintain the volume and consistency required for export. These losses can have lasting consequences as international buyers may shift to alternative suppliers, affecting market share and reputation beyond the immediate disaster period. As noted in a recent study,[46] the concentration of export production in specific regions can make entire countries vulnerable to disasters, affecting their key export areas, with consequences on foreign exchange earnings and economic development.

Secondary economic impacts are also generated in the financial sector through post-disaster adjustments in insurance and risk management costs, which influence agricultural investment and risk management decisions across entire sectors.[47] Similarly, public sector finances face dual pressures from disasters through increased expenditures for disaster response and recovery activities, while simultaneously experiencing reduced tax revenues from damaged economic sectors. These fiscal pressures can affect government capacity to provide agricultural support services, invest in rural infrastructure or fund disaster risk reduction measures, creating longer-term consequences for agricultural development and resilience building.[48]

ECONOMIC AND NON-ECONOMIC LOSS DIMENSIONS

While economic losses capture important dimensions of disaster impacts, the full consequences of disruptions to agrifood systems extend into non-economic realms that cannot be easily quantified in monetary terms but may have profound effects on individuals, communities and ecosystems. These non-economic losses often determine the long-term sustainability and resilience of agricultural systems. Among the most significant non-economic losses are those related to cultural heritage, including traditional farming practices, Indigenous crop varieties, and cultural landscapes that embody generations of agricultural knowledge and cultural identity accumulated through centuries of adaptation to local environmental conditions.[49] When traditional knowledge holders are displaced, environmental conditions change sufficiently to make traditional practices unviable. Likewise, the disruption of social structures that maintain cultural transmission may perpetuate permanent losses, reducing a community's capacity to adapt to environmental changes and manage agricultural risks using locally appropriate strategies.

Displacement, migration, breakdown of traditional support systems and competition for scarce resources can have profound effects on agricultural communities. Community institutions, including farmer organizations, cooperative societies, established governance structures, and informal mutual support networks may be weakened or fragmented following disasters. The erosion of social capital reduces a community's capacity for collective action, mutual support and collaborative resource management during crises, all of which are integral for agricultural sustainability.[50]

It is also challenging to quantify the cost of post-disaster changes in individual and collective well-being due to psychological and health impacts, including stress trauma, and mental health consequences experienced by farming communities affected by disasters. These impacts may persist long after physical damage is repaired and can affect productivity, decision-making, community cohesion, and overall quality of life in ways that are difficult to quantify but significantly influence recovery and adaptation processes.[51] These impacts may be particularly severe when disasters result in loss of life, destroy homes and personal property, or fundamentally disrupt livelihood systems that provide both economic security and cultural identity.

The environmental systems that support agriculture and provide ecosystem services and biodiversity are critical for agricultural sustainability, environmental health, and resilience and recovery from disasters, yet their non-economic monetary value is very difficult to quantify. Pollination services exemplify this challenge, as they may decline when habitat destruction reduces wild pollinator populations, when managed beekeeping operations are disrupted, or when pesticide use increases following disasters.[52] While the economic value of pollination services is substantial, their cultural and ecological significance extends well beyond monetary measures.

Similarly, the intricate balance of agricultural ecosystems relies on natural pest control services that regulate pest populations through predator–prey relationships and habitat management, reducing reliance on external pest control inputs while maintaining ecological balance.[53] Disaster-induced habitat destruction may reduce beneficial insect populations while creating conditions favourable for pest outbreaks, affecting both agricultural productivity and environmental sustainability. The restoration of natural pest control services may require ecosystem restoration efforts that extend far beyond agricultural areas, highlighting the interconnected nature of agricultural and natural systems in maintaining productive and sustainable farming landscapes.

In general, agricultural productivity is supported by complex biological processes, soil health and fertility services that maintain agricultural systems through nutrient cycling, organic matter decomposition and soil structure formation. Disasters can disrupt these processes through erosion, contamination, compaction or altered soil biology.[54] Similarly, disruptions to water regulation services, including watershed protection, groundwater recharge and flood control provided by natural ecosystems, can fundamentally affect agricultural water availability and quality.[55] Such impacts may not become apparent until subsequent growing seasons but can affect long-term agricultural sustainability and productivity.

The quantification of losses resulting from such indirect or non-economic services would require specialized methodologies and data collection tools that are currently not available. Nonetheless, it is important to recognize the trajectory of losses in these dimensions and to take into consideration longer-term processes and drivers that influence, and are in turn influenced by, disruptions to agrifood systems.

CLIMATE-DRIVEN RISKS

Long-term climatic shifts function as an overarching driver that intensify the onset of hazards, thereby contributing to the creation of new risk dimensions that challenge agricultural systems and disaster management practices. When it intensifies existing agricultural vulnerabilities, the result is compound risks that go beyond the impact of individual climate and non-climate stressors, fundamentally reshaping the risk landscape for agrifood systems worldwide. Understanding climate as a risk amplifier is essential for developing assessment methodologies and response strategies that can address current and projected future risks facing agricultural systems.

The most direct pathway through which climate affects disaster risk in agriculture occurs through the increased frequency and intensity of climate-related hazard events. Yet perhaps more concerning is how it pushes environmental conditions beyond critical limits for agricultural production.[56] When temperatures exceed heat tolerance thresholds for specific crops or livestock breeds, farming systems face discontinuous changes that customary adaptation strategies struggle to address. These threshold effects require shifts to heat-tolerant varieties, adjustments in production timing or the relocation of agricultural activities to more suitable geographic areas, making adaptation increasingly difficult and expensive, while potentially requiring fundamental transformations in how agriculture is practised.

Beyond its effects on biological systems, threatens the viability of agricultural infrastructure designed for historical climate conditions. Existing irrigation systems, natural water resources, and drainage infrastructure may prove inadequate in the context of changing precipitation patterns, necessitating significant investments in water management systems or fundamental changes in crop selection and farming practices. The challenge goes beyond total water availability to include the timing and intensity of precipitation events. More intense rainfall increases flood risks, while longer dry periods between events heighten drought stress, even when total annual precipitation remains adequate.

While sudden disasters capture immediate attention, slow-onset represent a particularly significant challenge that conventional disaster assessment frameworks often overlook, despite their potential to cause greater cumulative damage to agricultural systems over time. These gradual changes often fall below the threshold for emergency response systems designed for acute disasters, yet their cumulative impacts can fundamentally alter agricultural viability and rural livelihoods. The insidious nature of these changes makes them particularly dangerous, as communities may not recognize the need for adaptation until degradation has progressed beyond critical thresholds.

Among slow-onset climate processes, persistent drought and shifts in precipitation patterns stands out as the most significant threat to agricultural systems globally, creating progressive impacts that intensify over months or years while interacting with other environmental and economic stressors.[57] Initial effects of reduced soil moisture and water stress gradually diminish crop yields and pasture quality, but extended drought periods unleash cumulative impacts, including depleted groundwater resources, degraded soil structure, increased pest and disease pressure, and reduced livestock productivity due to inadequate food and water stress. Multiyear drought cycles create compound impacts that exceed the sum of individual season effects by depleting soil organic matter, reducing seed viability, destroying perennial crops and forests, forcing fundamental changes in farming systems and livestock management, and affecting regional water resources that support multiple users.

Desertification and land degradation exemplify how slow-onset processes affecting crops, livestock and forestry sectors proceed gradually through soil erosion, loss of organic matter, salinization and reduced vegetation cover.[58] These processes often begin slowly but accelerate under stress from resource overuse or mismanagement, climate variability or extreme weather events. Once advanced, desertification may become irreversible using currently available technologies and resources, resulting in the permanent loss of agricultural land and forcing population displacement from affected areas. The economic and social consequences of land degradation extend far beyond agriculture, affecting water resources, ecosystem services and rural livelihoods across entire landscapes.

Coastal agricultural systems face unique challenges from sea-level rise and coastal degradation, which impact agricultural areas through progressive saltwater intrusion, coastal erosion and increased flooding during storm events. These impacts typically develop over decades but accelerate during extreme weather events, resulting in the permanent or long-term loss of agricultural land in coastal areas while also affecting freshwater resources used for irrigation and livestock. The gradual nature of sea-level rise can make adaptation planning challenging, as the timing and magnitude of impacts remain uncertain, yet the irreversible nature of many coastal changes necessitates long-term planning and potentially expensive adaptation measures.

As changing climate patterns disrupt natural systems, the ecosystem services essential for agricultural productivity face unprecedented challenges, creating indirect impacts that can be difficult to anticipate and manage. Forest ecosystems may experience dieback that reduces watershed protection and carbon storage while increasing fire risk that threatens agricultural areas and rural communities. Changes in pest and disease dynamics expose crops and livestock to new threats while reducing the effectiveness of existing management strategies. Gradual shifts in temperature and precipitation patterns also create changes in agricultural suitability that affect crop selection, growing season timing, irrigation requirements and pest management strategies without necessarily triggering emergency response systems. These changes may benefit some regions while harming others, but often require significant adaptation investments and technical knowledge that may not be readily available to vulnerable farming communities.

The human dimensions of shifting climate patterns manifest through the contribution to migration patterns that can create social tensions affecting agricultural labour availability and community stability, while also putting pressure on destination areas that may already be experiencing environmental stress. Competition for scarce water or land resources increases conflict risk while reducing the cooperative resource management that supports agricultural sustainability. Economic stress from climate impacts reduces the capacity for adaptation investments, creating negative feedback loops that increase vulnerability over time.

The intricate web of interactions between climate and ecosystem processes creates unprecedented uncertainties that challenge conventional risk assessment and management approaches. As climate events affect multiple environmental and social systems simultaneously, compound and cascading risks emerge that amplify when combined with population growth, economic development pressures, political instability or environmental degradation from non-climate sources. The resulting risk scenarios can overwhelm adaptive capacity, creating tipping points where agricultural systems lose resilience and the ability to recover from additional stresses, ultimately leading to permanent changes in productivity, viability or sustainability. Understanding these complex interactions requires loss assessment approaches that capture multiple stressors and their synergistic effects, rather than treating changing climate patterns as an isolated risk factor. The future of agrifood systems depends on our ability to comprehend and respond to these interconnected challenges.

OVERSIGHTS AND LIMITATIONS OF ASSESSMENT TOOLS

A critical dimension of the limitations of loss assessment exercises lies in their lack of consideration of social vulnerabilities, which represent the experiences and needs of women, Indigenous Peoples, ethnic minorities and other vulnerable groups in agricultural communities. Such oversights reflect both methodological limitations and institutional biases that fail to capture the differentiated impacts experienced by diverse population groups and may inadvertently perpetuate inequalities and undermine the effectiveness of disaster response and recovery efforts by reinforcing existing disparities rather than promoting more equitable outcomes.

Within agrifood systems, disaster impacts experienced by women mirror structural inequalities that influence exposure to disaster risks, access to resources for protection and recovery, and participation in decision-making processes that determine response strategies and resource allocation. Women often bear disproportionate responsibility for food production, post-harvest processing and household food security, yet have limited control over productive resources, financial assets, and income-generating opportunities that significantly impact their ability to prepare for and recover from disasters.[59,60] According to a report by FAO in 2024,[61] rural female-headed households lose around 8 percent more of their income due to excessive heat events, and 3 percent more due to floods.

The agricultural roles typically performed by women often involve activities that are particularly vulnerable to climate extremes, including small-scale crop production, livestock management, and food processing and preservation activities, which may face greater exposure to environmental stresses than larger-scale, more capital-intensive agricultural operations. Additionally, women's responsibility for water collection, fuelwood gathering, and household food preparation increases their exposure to environmental stresses while limiting their ability to engage in alternative livelihood activities during and after disasters.

Compounding these vulnerabilities, decision-making constraints limit the ability of women to access and implement protective and preparedness measures before disasters, evacuate to safer locations during emergencies, or participate in recovery planning processes that determine how communities rebuild and adapt following disaster events.[62] Traditional social roles may restrict women's mobility, limit their participation in public meetings, or exclude them from formal decision-making institutions that control resource allocation and recovery planning. For example, restricted participation in farmer organizations and cooperatives affects access to information, technical assistance and collective action opportunities that can enhance resilience.[63] It is estimated that until recently, women only received 5 percent of agricultural extension services at a global level.[64] Furthermore, limited land ownership and tenure security reduce women's control over agricultural assets while constraining their access to credit, insurance, and other financial services that support disaster preparation and recovery.

The vulnerabilities of Indigenous Peoples and other minority communities often remain invisible in standard assessment approaches that employ mainstream frameworks and indicators without considering culturally specific impacts, priorities, capacities and coping strategies that may be more appropriate for particular communities. When displacement, environmental change or social disruption interrupts the transmission of agricultural knowledge between generations, traditional knowledge systems face disruption, reducing community capacity for culturally appropriate adaptation and resilience-building.

For these communities, cultural heritage impacts extend beyond material losses to include traditional crop varieties, livestock breeds, and agricultural practices that embody generations of accumulated knowledge and cultural identity, while providing genetic resources crucial for climate adaptation. Sacred sites and cultural landscapes may suffer damage or destruction, affecting spiritual well-being and cultural continuity in ways that are harder to quantify but significantly impact community resilience and recovery capacity.

Institutional barriers further marginalize Indigenous Peoples and minority communities by constraining their participation in formal disaster management systems while limiting access to government services and assistance programmes that may not be culturally appropriate or accessible. Language barriers can also prevent access to early warning information, technical assistance and recovery support, while discrimination in service access may result in inadequate or inappropriate assistance that fails to meet community needs and priorities.

Vulnerabilities related to age, ethnicity, disability, and migration or citizen status create additional layers of differential impacts that require specialized assessment approaches, yet standard protocols often overlook these factors.[65] Children and youth face disrupted education and skill development that affects their long-term agricultural capacity and innovation potential, while elderly populations may encounter physical limitations, reducing their disaster response ability despite possessing traditional knowledge critical for community resilience.

These assessment methodology gaps become particularly evident through data aggregation practices that mask intra-household and intra-community inequalities by concentrating on household-level impacts without examining differential effects on various family members or community groups. Systematic underrepresentation of women and other minority groups' experiences and priorities in standardized indicators leads to a failure in capturing intersectional, culturally specific impacts and priorities important for Indigenous Peoples and minority communities.

Perhaps one of the most significant yet overlooked assessment challenges involves biodiversity and ecosystem services, as existing disaster impact assessments rarely address impacts on agricultural biodiversity and ecosystem services despite their fundamental importance for agricultural sustainability, resilience and long-term productivity.[66] This oversight stems from both conceptual limitations in understanding agricultural systems as components of broader ecological systems and practical challenges in measuring and valuing ecosystem services that lack established market prices.

The scope of agricultural biodiversity encompasses the variety and variability of animals, plants, and microorganisms used directly or indirectly for food and agriculture, including crop varieties, livestock breeds, forest species, fish species and their wild relatives that provide the foundation for adaptation to changing environmental conditions. This genetic diversity represents a critical component of agricultural resilience frequently overlooked in disaster impact assessments focused on immediate production losses and economic damage.[67]

The broader category of ecosystem services represents benefits people derive from natural ecosystems, including services directly supporting agricultural production and those contributing to environmental stability and human well-being. Provisioning services encompass genetic resources, freshwater and soil formation that directly support agricultural activities, while regulating services include climate regulation, water purification, pest control and pollination, which maintain the conditions necessary for productive agriculture.[68] Disaster impacts that affect these services may remain latent until subsequent growing seasons but can affect long-term agricultural sustainability and productivity in ways exceeding immediate production losses.

When disasters strike, crop genetic diversity faces severe threats. Disasters destroy seed stocks, disrupt established seed-saving and exchange systems or force farmers to adopt uniform commercial varieties during recovery periods when traditional varieties may remain unavailable. Local crop varieties and landraces adapted to specific environmental conditions risk permanent loss when seed stocks suffer destruction and replacement seeds cannot be obtained from established sources, thereby reducing long-term adaptive capacity and eroding cultural heritage.[69]

The disruption of existing seed systems, which maintain agricultural biodiversity through farmer-to-farmer exchange, occurs through displacement, social disruption, or economic stress that forces farmers to rely on commercial seed sources potentially unsuited to local conditions or incompatible with traditional farming practices. Extreme climate events compound these challenges by making conventional varieties unsuitable for new environmental conditions while exerting pressure to adopt new varieties that may poorly match local social and economic contexts.

Livestock genetic resources encounter similar threats when disasters cause disproportionate mortality among locally adapted breeds, while forcing farmers to restock with commercial breeds potentially less suited to local environmental and management conditions. Long-established breeding programmes and selection practices suffer disruption through displacement, loss of breeding animals, or breakdown of community institutions that manage genetic resources and maintain breed characteristics.

Beyond domesticated species, wild biodiversity in agricultural landscapes experiences impacts affecting ecosystem services essential for agricultural productivity while contributing to global biodiversity conservation goals extending beyond agricultural production. Beneficial organisms, including pollinators, natural enemies of agricultural pests and soil microorganisms, may also experience population declines following habitat destruction, pesticide contamination, or disrupted ecological relationships affecting agricultural productivity and environmental sustainability.

The challenge of assessing biodiversity and ecosystem services encounters multiple obstacles, beginning with valuation difficulties. Many ecosystem services lack established market prices enabling direct economic quantification, which makes their incorporation into standard economic impact assessments problematic.[70] Temporal dynamics introduce additional complexity as ecosystem impacts may emerge gradually over months or years following initial disaster events, necessitating long-term monitoring and assessment approaches extending beyond immediate post-disaster periods.

Spatial complexity emerges because ecosystem services operate across multiple scales from local pollination services to regional watershed protection and global climate regulation, requiring assessment approaches capable of capturing impacts across different spatial and temporal dimensions. These interdisciplinary requirements demand expertise spanning ecology, economics and social sciences that standard disaster assessment teams may lack, creating capacity constraints that limit comprehensive ecosystem assessment capabilities.

The cumulative effect of these assessment gaps and limitations extends far beyond technical inadequacies, fundamentally undermining our ability to understand and respond to the complex ways disasters affect agrifood systems and the communities that depend on them. Without comprehensive assessment frameworks that capture production system impacts, social vulnerabilities, and ecosystem service impacts across multiple scales and timeframes, disaster responses will continue to address symptoms rather than root causes, potentially exacerbating inequalities and environmental degradation, while missing opportunities for building more resilient and sustainable agrifood systems. Addressing these limitations requires more than incremental improvements to existing methodologies. It calls for a fundamental reconceptualization of how we understand and assess disaster impacts on agriculture, integrating diverse knowledge systems, recognizing differential vulnerabilities, and acknowledging the interconnected nature of agricultural, social and ecological systems. Only through such comprehensive approaches can assessment tools fulfil their potential to inform effective, equitable, and sustainable disaster risk reduction strategies that support efforts to enhance the resilience of agrifood systems and rural communities facing an increasingly uncertain future. ■

2.2 IMPACT MONITORING TOOLS AND GAPS

The previous section lays out the main trajectories, dimensions and drivers of the transmission of disaster impacts across agrifood systems, and the challenges of measuring these impacts. In principle, assessing disaster impacts on agriculture would require some form of measurement – economic or non-economic – of the negative consequences experienced in all the affected components of agrifood systems. However, undertaking such an assessment – especially at the global scale – is problematic owing to the lack of relevant, consistent, up-to-date and reliable data; the complex and interconnected nature of agrifood systems; and the potential for localized disaster events to have widespread or indirect consequences. As a result, substantial gaps remain in our ability to measure and quantify the full scope of how disasters affect agrifood systems, which constrains our understanding of disaster consequences and limits the effectiveness of response and recovery efforts.

Efforts are being made to address this gap, and methodologies for assessing disaster impacts in agriculture have evolved significantly over recent decades, incorporating lessons learned from major disaster events, advances in scientific understanding of agricultural systems, and improvements in data collection and analysis technologies. Data limitations and the absence of specialized repositories for documenting disaster impacts on agrifood systems present the primary challenge for undertaking loss evaluations. Current assessment approaches therefore focus primarily on assessing immediate economic losses and cannot yet account for the complex, indirect and cascading effects that ripple through interconnected agrifood systems after a disaster event. Although this leads to a systematic underestimation of disaster impacts on agriculture, these loss assessments serve as foundational frameworks for identifying vulnerabilities and allocating resources for recovery and resilience-building.

GLOBAL MONITORING FRAMEWORKS AND IMPLEMENTATION

Specialized agricultural assessment tools have been developed to address specific aspects of disaster impacts but are often limited to specific hazards, impact types or agricultural subsectors. The following section outlines the two principal tools available for monitoring the impact of disasters at a global scale that also contain information on sectoral losses in agriculture.

Sendai framework monitor indicator C2

The Sendai Framework for Disaster Risk Reduction 2015-2030 provides the primary global framework for monitoring disaster impacts and tracking progress towards reducing disaster risk and losses. Its indicator system aims to standardize impact measurement across countries and sectors, with Global Target C specifically formulated to measure direct economic losses caused by disasters in relation to global gross domestic product.[71] Agricultural losses are a critical component of Target C, and FAO has provided support to the UNDRR for the development of a methodology for reporting direct agricultural losses attributed to disasters under the C2 indicator of the Sendai Framework Monitor.[72] The methodology provides standardized definitions and assessment indicators that enable subsectoral analysis, cross-country comparison and global aggregation of disaster impacts in agriculture.

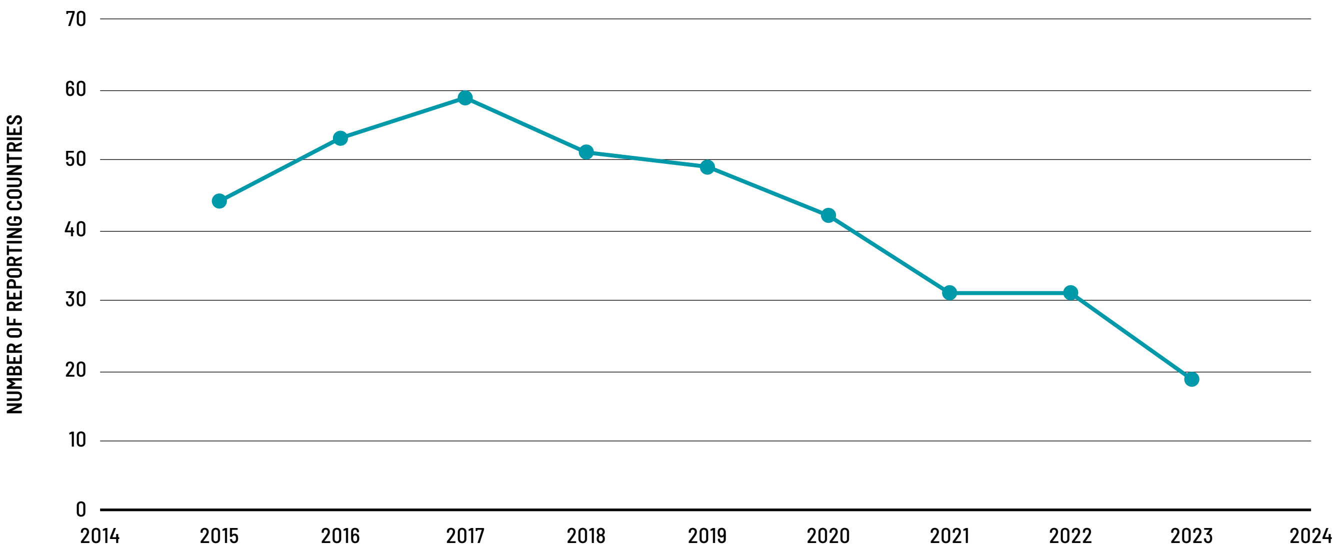
The indicator system relies on voluntary annual reporting by Member States through the Sendai

Framework Monitor, creating a baseline and longitudinal datasets that support comparative analysis and progress tracking of disaster losses over time. The implementation of the Sendai Framework Monitor reveals progress in efforts by countries to establish standardized monitoring systems and develop national disaster loss databases for systematic impact monitoring. But it also highlights persistent challenges in data collection and analysis, as well as the institutional capacities of countries that limit the scope of global monitoring efforts. While agricultural loss reporting by member states has expanded since the framework's adoption, with a total of 87 countries reporting at least once under indicator C2 since 2015, the overall number of reports is relatively low and the number of countries reporting has considerably declined in recent years (see FIGURE 1).

Substantial gaps in country coverage, data quality and reliability, and analytical capacity constrain the effectiveness of global monitoring systems, such as the Sendai Framework Monitor. In parallel with tools for monitoring losses, countries need support in increasing technical capacity, financial resources, and establishing institutional frameworks necessary for systematic monitoring and assessment of disaster impacts. Without these, there are likely to be significant data quality variations in the reported information, limiting the reliability and comparability of data and resulting in significant underreporting and underrepresentation of disaster impacts in agriculture. The losses declared under the C2 indicator (FIGURE 2) are therefore informative but not necessarily representative of agricultural loss trends at a global level due to inconsistent and under-reporting of data.

Although the C2 indicator reporting structure allows for the possibility to report disaggregated values for vulnerable groups, geographic areas and impact types, there is limited reporting by countries under these categories. The data also allows for the disaggregation of losses by hazard types (FIGURE 3), however, only 10 percent of countries have provided information on the type of hazard associated with reported agricultural losses. The information is therefore partial and incomplete, but it still points to the dominance of hydrometeorological events such as storms, floods, heatwaves and droughts in afflicting losses in agriculture.

FIGURE 1
NUMBER OF COUNTRIES REPORTING UNDER SENDAI FRAMEWORK INDICATOR C2

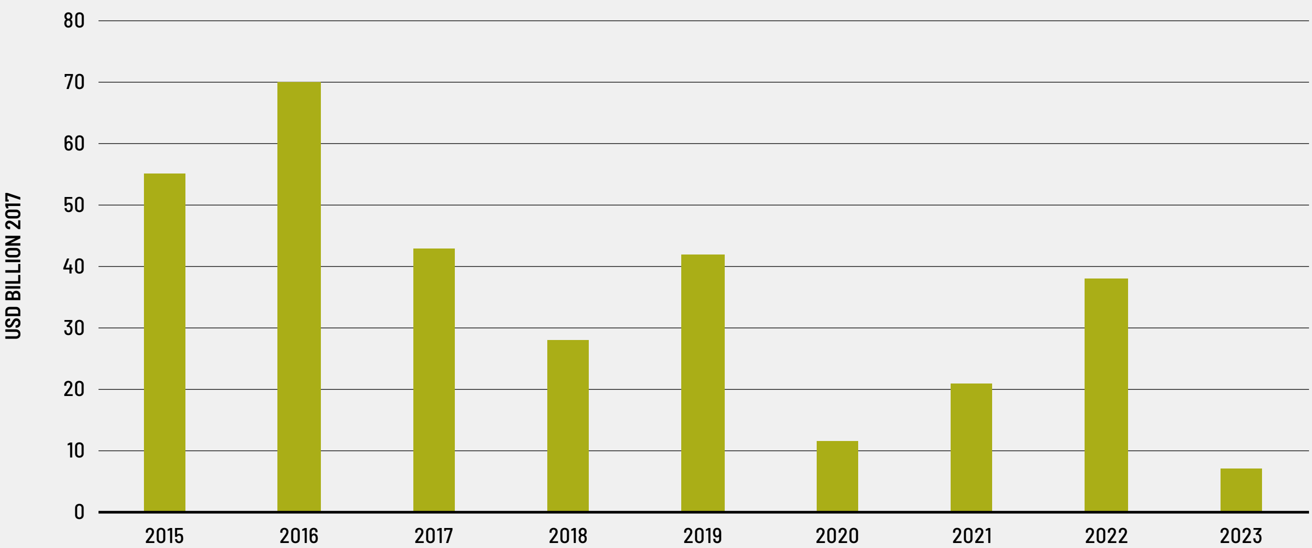


Source: Authors' own elaboration based on Sendai C2 indicator data provided by UNDRR.

https://doi.org/10.4060/cd7185en-fig01

As the C2 indicator was designed to capture direct economic losses in agriculture, it does not include indirect effects, non-economic losses and longer-term consequences that may be more significant than immediate damages. To address this gap, the UNDRR launched the Disaster and Hazardous Events, Losses, and Damages Tracking and Analysis System (DELTA Resilience) in June 2025 to provide a more comprehensive and methodologically advanced tool for recording disaster losses.[73] The new tool, discussed in greater detail in **Part 3** of the report, is a groundbreaking collaboration between UNDRR, the United Nations Development Programme (UNDP), and the WMO that will replace the legacy DesInventar platform with a comprehensive, interoperable solution that tracks both hazardous events and

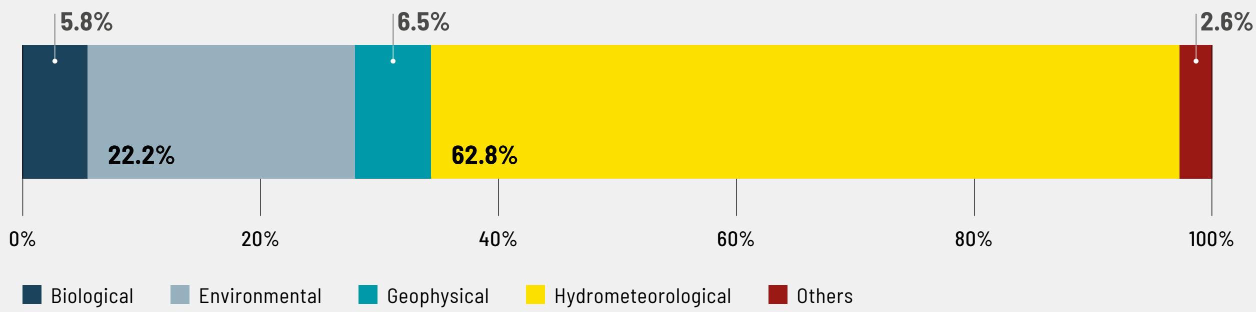
FIGURE 2
AGRICULTURAL LOSSES DECLARED UNDER SENDAI FRAMEWORK INDICATOR C2



Source: Authors' own elaboration based on Sendai C2 indicator data provided by UNDRR.

https://doi.org/10.4060/cd7185en-fig02

FIGURE 3
SHARE OF IMPACT BY HAZARD TYPE DECLARED UNDER SENDAI FRAMEWORK INDICATOR C2, 2015–2023



Source: Authors' own elaboration based on Sendai C2 indicator data provided by UNDRR.

https://doi.org/10.4060/cd7185en-fig03

disaggregated losses at localized scales.

The system's foundation rests on building synergy with the WMO-CHE methodology, creating unprecedented connections between meteorological observations and disaster impacts, including cascading effects across multiple sectors. A key innovation is the DELTA Resilience system's emphasis on institutional collaboration. Linkages and enhanced collaboration between the national disaster management offices (NDMOs), the national hydro-meteorological services (NHMS), and the national statistics offices (NSOs) extend the losses and damages data value chain to support improved analytical options and enable data use. This multi-agency approach addresses the fragmented nature of conventional disaster data collection.

The system incorporates advanced technological solutions designed for varying digital maturity levels. Technology tools such as application programming interfaces (APIs) and post-processing tools will be part of the digital technology solutions available to enable countries to migrate and map historic data to new classification and data standards. The tool will be made available to Member States as a downloadable software system to establish country-owned, institutionalized and contextualized national losses and damages tracking systems.

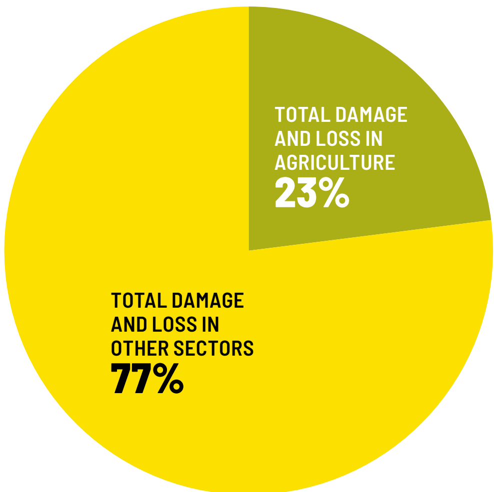
Post-disaster needs assessments

PDNAs offer an international survey structure for the comprehensive assessment of disaster impacts and recovery needs across multiple sectors, with specialized approaches developed for agricultural sector assessment that integrate physical damage evaluation with socioeconomic impact analysis and recovery planning. The methodology provides a harmonized approach for disaster impact assessment through standardized frameworks that capture damage to physical assets, losses in economic flows, human impacts on affected populations, and recovery needs for restoration and improvement of affected systems.[74]

The PDNA survey follows established phases, including preparation, field assessment, analysis, and reporting that ensure systematic and comprehensive evaluation of disaster impacts while building national capacity for disaster assessment and management. Government leadership ensures national ownership and policy relevance while multi-agency participation brings diverse technical expertise and resources to assessment efforts. Standardized questionnaires enable rapid deployment of assessment teams while ensuring consistency and quality of results across different contexts and disaster types.

Agricultural sector applications include specialized assessment protocols for crops, livestock, fisheries and aquaculture, and forestry subsectors that account for the unique characteristics and vulnerabilities of each agricultural activity while providing standardized approaches for quantifying impacts and identifying recovery priorities. Although the information contained in PDNAs is not representative due to the limited number of surveys conducted – usually in low-income countries and after the most damaging disaster events – the availability of information on sectoral losses allows for comparison between the cost inflicted by disasters in different economic sectors. Findings from 96 PDNAs undertaken during the 2007–2024 period in 63 countries (see Annex 1) show that agricultural losses make up an average of 23 percent »

FIGURE 4
SHARE OF SECTORAL LOSSES

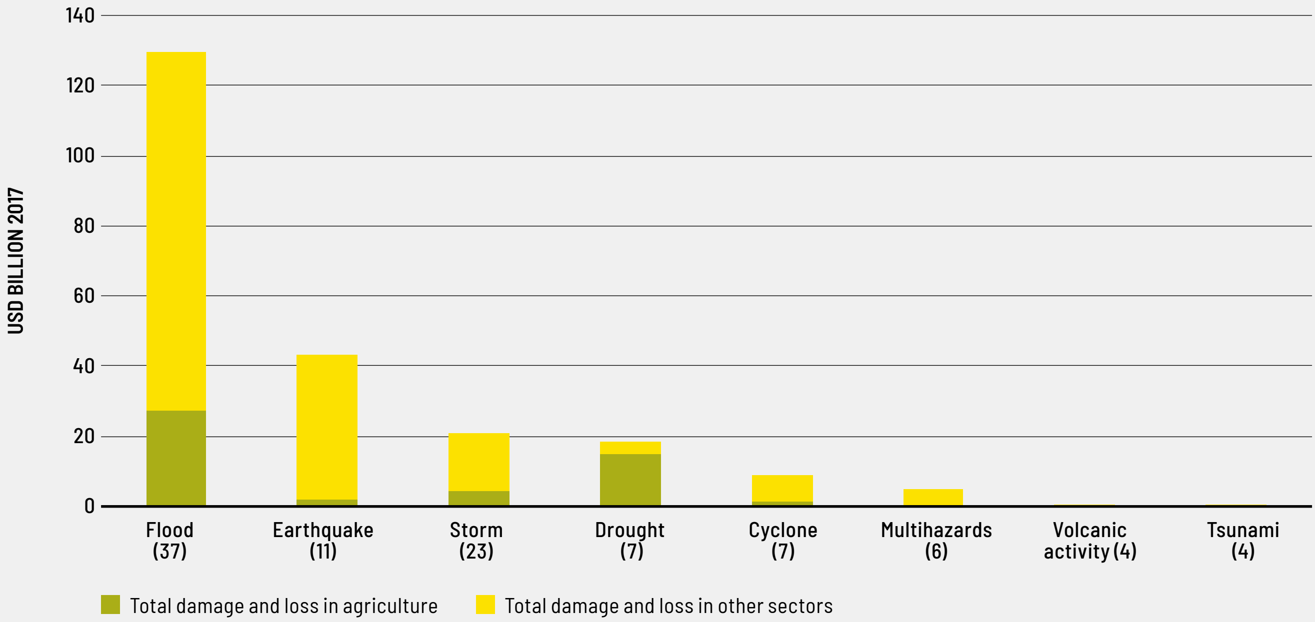


Note: See **Annex 1**.
Source: Authors' own elaboration based on data derived from PDNAs.

https://doi.org/10.4060/cd7185en-fig04

FIGURE 5

ECONOMIC LOSS IN AGRICULTURE AND NON-AGRICULTURAL SECTORS BY HAZARD TYPE (VALUE)

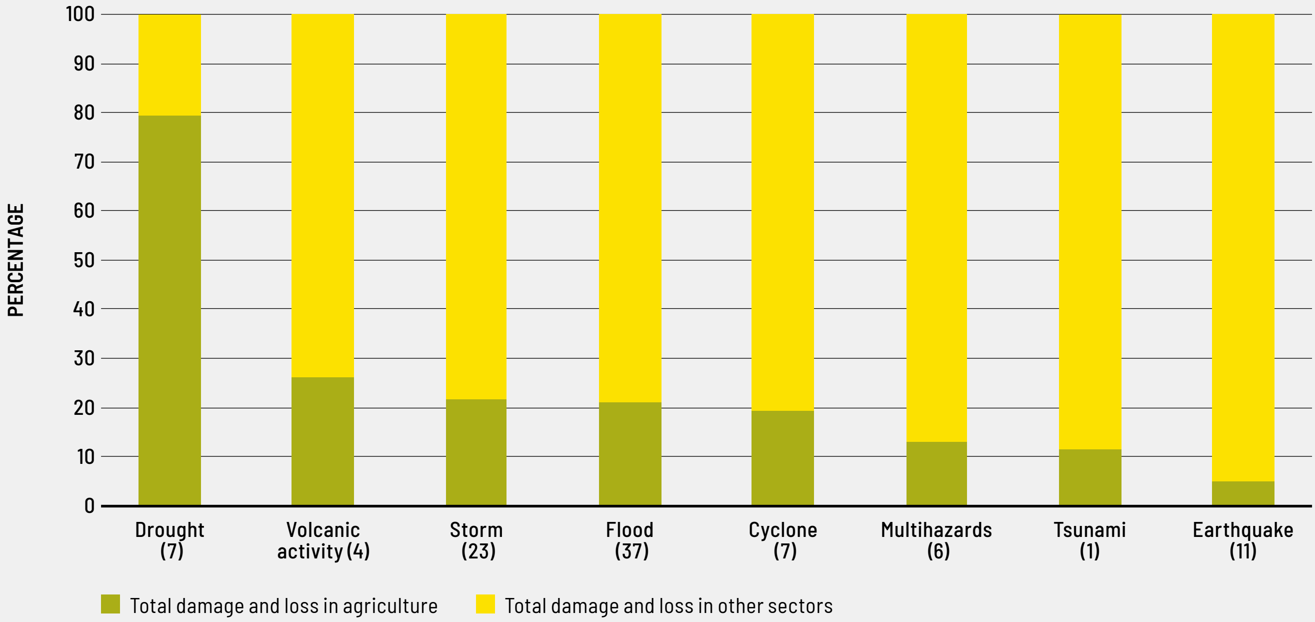


Note: See **Annex 1** for the methodology. Numbers in brackets represent the total number of recorded events for each hazard type.
Source: Authors' own elaboration based on data derived from PDNAs.

https://doi.org/10.4060/cd7185en-fig05

FIGURE 6

ECONOMIC LOSS IN AGRICULTURE AND NON-AGRICULTURAL SECTORS BY HAZARD TYPE (SHARE)



Note: See **Annex 1** for the methodology. Numbers in brackets represent the total number of recorded events for each hazard type.
Source: Authors' own elaboration based on data derived from PDNAs.

https://doi.org/10.4060/cd7185en-fig06

» of the total impact of disasters across all sectors (FIGURE 4).

Data from PDNAs can also help assess how different hazards impact agriculture, although such data must be interpreted with caution due to their inherent limitations. Since PDNAs are conducted only after select disaster events, their utility as a systematic data source is limited, especially for estimates of disaster-induced losses across the full spectrum of hazard types. Additionally, the extent of agricultural losses after each disaster event is context-specific and can vary depending on several factors, including the type and strength of the hazard, its timing relative to crop cycles, and the specific ecological and geographical setting. Notwithstanding these limitations, data from PDNAs indicate that while floods cause the greatest total economic damage to agriculture (see FIGURE 5), droughts result in the highest proportion of loss within the sector, accounting for nearly 80 percent of agriculture's share of losses compared to other economic sectors (see FIGURE 6). This finding is significant because droughts are typically underreported in disaster databases like the EM-DAT, and far fewer PDNAs have been conducted following drought-related disasters than after floods or storms. If more PDNAs were carried out in response to drought events, the reported agricultural losses would likely be substantially higher.

Overall, the PDNA survey constitutes a resource-intensive exercise that requires significant technical expertise, time, and financial resources that may not be readily available following major disasters when immediate response needs compete for attention and resources. The focus on immediate post-disaster periods may also miss longer-term agricultural impacts that emerge over months or years following initial events, particularly for perennial crops, livestock breeding stock and ecosystem services that require extended periods for recovery or may experience delayed effects. Recent efforts to revise the methodology include consideration of slow-onset events and gradual environmental processes that may cause cumulative damage, and recognition of non-economic losses and indirect effects that significantly affect community resilience and recovery capacity. ■

2.3 GLOBAL ASSESSMENT AND SECTORAL ANALYSIS OF LOSSES

Systematic measurement and quantification of disaster impacts provide essential evidence for understanding the magnitude and patterns of agricultural losses, while informing policy development, resource allocation and risk reduction planning across multiple scales, from local to global. However, most countries lack systematic data collection systems for recording agricultural production and disaster impacts, resulting in significant gaps in data availability and quality that can limit the accuracy and completeness of impact estimates. Differences in data standards, statistical capacity, institutional arrangements, and resource availability for monitoring disaster impacts result in variations in data quality across countries and regions. These limitations restrict the utility of global monitoring tools, such as the Sendai C2 Indicator and the PDNA surveys, in providing evidence on loss trends, as they are largely dependent on the quantity and quality of data collected and reported under their respective frameworks.

In the absence of consistent historical datasets on realized disaster losses in agriculture, modelled estimations of impacts can provide an alternative approach to understanding agricultural risk and vulnerabilities. The quantitative assessment presented in this report represents a significant step forward in estimating direct economic losses in agriculture from 1991 to 2023, using the global agricultural production dataset from FAOSTAT and disaster event records from the EM-DAT database to calculate production losses in crops and livestock. The analysis reveals important patterns in how disasters affect different agricultural subsectors and geographic regions, providing valuable insights into the distribution of vulnerability and risk concentrations. The findings demonstrate both the significant scale of disaster impacts and the substantial variations in loss patterns across different agricultural subsectors, geographic regions and hazard types, reflecting the complex interactions between hazard characteristics, exposure patterns, vulnerability factors and response capacities that determine impact outcomes.

However, the results also underscore the substantial data gaps that continue to constrain our understanding of disaster impacts in agriculture, particularly for the fisheries and forestry subsectors, where a lack of systematic data prevents a comprehensive analysis of disaster losses despite the significant economic, social, and environmental importance of these sectors for rural livelihoods and food security. The challenges encountered in conducting comprehensive impact assessments highlight the need for enhanced data collection systems, improved analytical methodologies, and strengthened institutional capacity for systematic disaster impact monitoring and analysis.

DIRECT ECONOMIC LOSSES IN CROPS AND LIVESTOCK

The quantitative assessment of direct economic losses in crops and livestock presented in this section utilizes agricultural production data available from FAOSTAT for crops and livestock commodity items, combining it with historical records of global disaster events recorded in the EM-DAT disaster database. To estimate disaster losses in agriculture on a global scale over 1991–2023, counterfactual yields were estimated for non-disaster years for 191 items and 205 countries and territories (see Annex 1). The differences between the estimated counterfactual yields and the actual yields correspond to disaster-induced yield losses, after filtering by significance levels. Using the yield losses estimated for a particular item at the country level, production losses in tonnes and economic losses in 2017 USD were calculated.

The results reveal patterns that demonstrate the significant scale of disaster losses in agriculture, totalling USD 3.26 trillion, and the increasing magnitude of these losses over the last 33 years. Of this total loss, nearly USD 2.9 trillion was attributed to climate-related hazards, including floods, droughts and heatwaves, highlighting the significant impact of climate-related extreme events on the agricultural sector. The data reveal three distinct phases (see FIGURE 7): moderate losses in the 1990s, averaging USD 64 billion annually; gradual increases throughout the 2000s, reaching USD 67 billion per year; and a severe escalation from 2010 onwards, with losses reaching USD 144 billion annually. This amounts to an average annual loss of USD 99 billion over the last 33 years. Although the sharp increase after 2010 can partly be explained

BOX 1

METHODOLOGICAL IMPROVEMENTS AND AMENDMENTS

Several updates have been made to strengthen the model and improve how agricultural losses are estimated. A new error identification scheme was introduced, which helps calculate both the estimated value of losses and the confidence intervals around those estimates. The model now also applies hypothesis testing at a 5 percent significance level, making the results more reliable and transparent.

Economic losses are now reported through two key components: yield losses, as in previous editions, and a new measure that captures losses linked to reductions in livestock numbers.

A sensitivity analysis was carried out to see whether changes in land use affected productivity independently of production levels. The results showed no significant effect, suggesting that most productivity losses are driven by production-related factors rather than changes coming from cultivated land.

To improve consistency, the number of country clusters used in the model was reduced from 20 to 5. This change, based on heuristic methods, helps ensure that countries within each cluster are more similar, making the regression results more robust and reliable.

Together, these improvements led to a re-estimation of loss figures for the 2023 report. The updated model shows a lower global total of losses and a refined picture of regional and subregional trends. In addition, the price dataset in FAOSTAT was updated to correct the consumer price index (CPI), which affected the total economic loss estimates for 2025.

Source: Authors' own elaboration.

by the improved reporting of disaster events in the EM-DAT database, it also coincides with the intensification of climate-related disasters globally.

Notable peak years include 2012 (USD 138 billion), 2014 (USD 147 billion), 2019 (USD 173 billion), 2021 (USD 192 billion) and 2022 (USD 215 billion). These spikes are a result of lost production in various agricultural commodity groups, as major drought events, flooding episodes, and extreme weather patterns have affected crops and livestock production globally. For example, a major driver of economic losses in 2012 (FIGURE 7) appears to be extreme cereal losses in the same year (see FIGURE 8). In fact, the United States of American experienced a multibillion-dollar agricultural disaster caused by a La Niña-induced drought event in 2012. The "Great Drought" of 2012 resulted in a 27 percent reduction in maize production and a nearly 26 percent decline in sorghum production, with overall agricultural losses exceeding USD 30 billion.[75]

Similarly, economic losses increased in 2019 and have remained at relatively high levels since then. This is due to the combined effect of volatility in prices and agricultural commodity markets created by the COVID 19 pandemic, and an increasing number of extreme weather events that affected agricultural production in several countries, especially the extraordinary "triple La Niña" event that took place between 2020 and 2023. For example, the La Niña-related floods in Southeast Asia, Australia and Canada and drought in South America resulted in a decrease in the production of oilseeds such as rapeseed, soybeans, and palm of between 30 and 40 percent.[76,77]

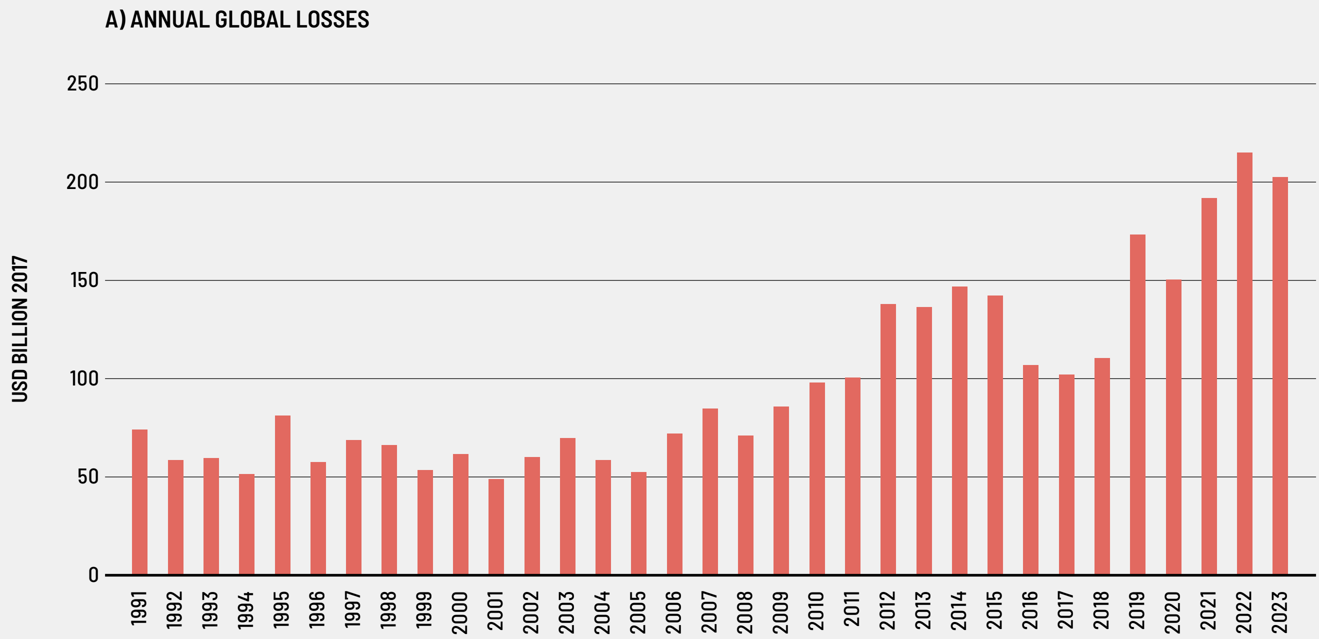
An examination of physical production losses reveals that cereals are the most severely impacted commodity group, with total cumulative losses of 4.6 billion tonnes over the analysis period, followed by fruits, nuts and vegetables (2.8 billion tonnes), and with meat, dairy and eggs losing 0.9 billion tonnes (see FIGURE 8). The scale demonstrates the massive impact of disasters on global food production systems. Cereals also exhibit significant variability in annual production losses, with substantial declines in production quantities in 2012 (314.7 million tonnes) and 2013 (227.5 million tonnes), reflecting the sector's high sensitivity to climate variability and climate-related extreme events.[78]

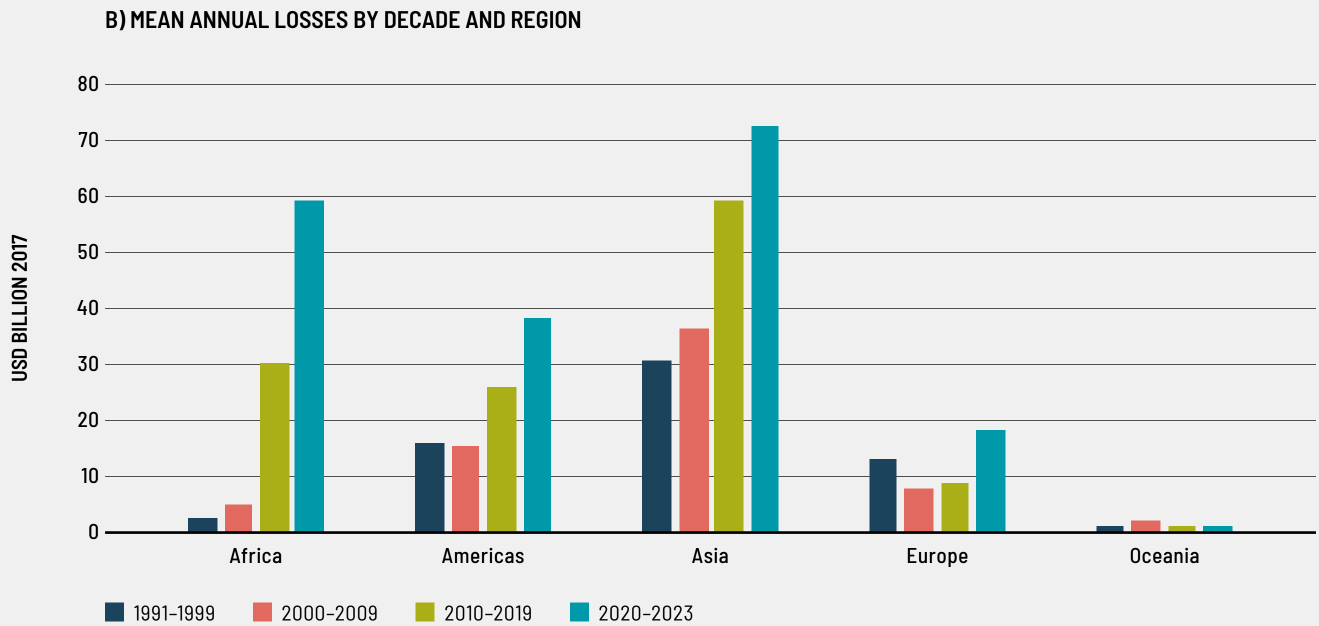
A comprehensive breakdown of losses by region demonstrates that Asia shoulders the heaviest burden of agricultural disaster losses, accounting for nearly half of all global losses at 47 percent, equivalent to USD 1.53 trillion (see FIGURE 9). This substantial amount reflects not only Asia's vast agricultural sector and large rural populations but also the region's heightened vulnerability to climate-related disasters, such as typhoons, floods, droughts and monsoon variability. The Americas follow as the second-most affected region, experiencing nearly 22 percent of global agricultural losses, totalling USD 713 billion. This significant impact spans the hurricane-prone Caribbean and Central American regions to the drought-susceptible agricultural heartlands of North and South America, where extreme weather events increasingly threaten crop production and livestock systems.

Africa accounts for 19 percent of global agricultural disaster losses, amounting to USD 611 billion – an amount that carries profound implications for food security across the continent. Given that agriculture employs a large portion of Africa's workforce and many countries depend heavily on rain-fed agriculture, these losses represent not just economic damage but also threats to livelihoods and food security for millions of people. Europe experiences 11 percent of global losses, equivalent to USD 353 billion, despite having more developed agricultural infrastructure and disaster preparedness systems. This demonstrates that even technologically advanced regions with robust early warning capacities and coping mechanisms are not immune to the mounting impacts of disasters on agricultural productivity. Oceania, while experiencing the lowest relative losses at 2 percent (USD 49 billion), still faces significant challenges given the region's smaller agricultural base and unique vulnerabilities to droughts, wildfires and cyclones that can devastate entire farming communities.

The relationship between agricultural productivity and disaster losses reveals a »

FIGURE 7
TOTAL ESTIMATED AGRICULTURAL PRODUCTION LOSSES



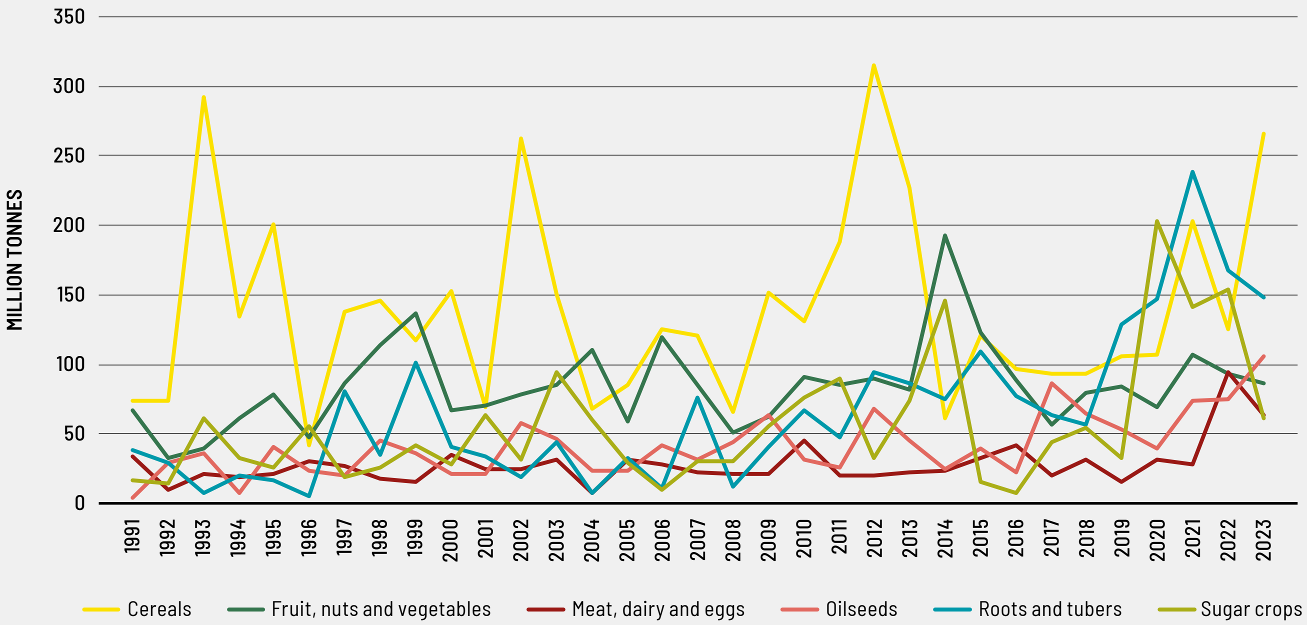


Source: Authors' own elaboration based on FAO data.

https://doi.org/10.4060/cd7185en-fig07

FIGURE 8

ESTIMATED LOSSES IN MAIN PRODUCT GROUPS

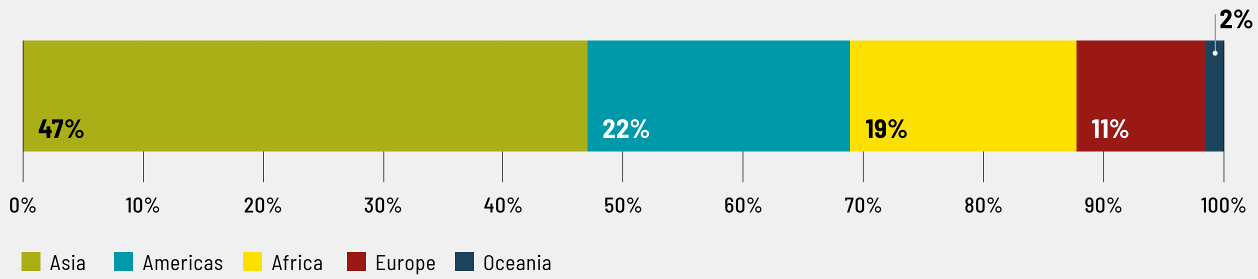


Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig08

FIGURE 9

DISTRIBUTION OF ESTIMATED LOSSES BY REGION, 1991–2023

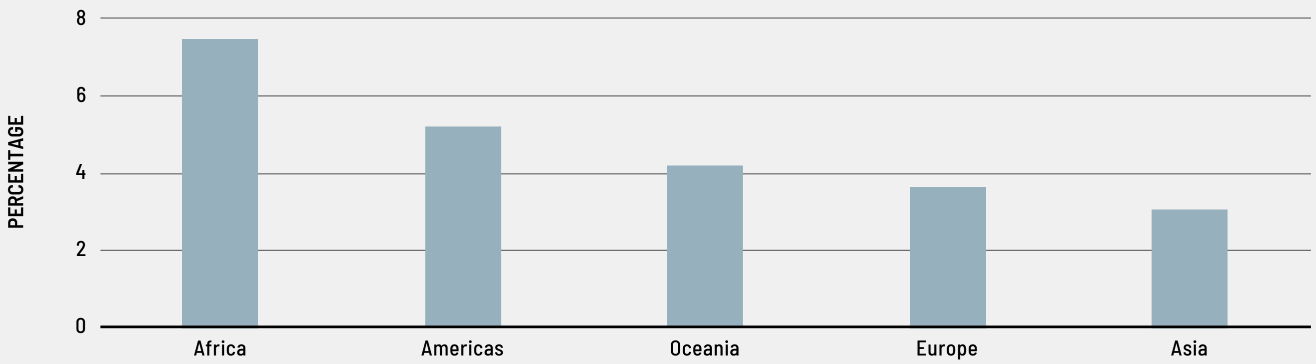


Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig09

FIGURE 10

LOSSES AS A SHARE OF AGRICULTURAL GROSS DOMESTIC PRODUCT, 1991–2023



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig10

» nuanced pattern that extends far beyond simple geographic distribution. Regions with high agricultural productivity and significant economic importance in the global food system tend to incur substantially larger absolute losses when affected by disasters, as exemplified by Asia's staggering USD 1.53 trillion in losses. This phenomenon directly reflects Asia's leadership in global agricultural production and the concentration of agricultural resources across the continent, where countries such as China, India, and Indonesia maintain vast agricultural sectors that support billions of people and contribute significantly to global food security.

The scale of these losses is intrinsically linked to the sheer magnitude of agricultural assets at risk. When disasters strike highly productive agricultural regions, the economic impact is amplified by the density of crops, livestock, infrastructure, and processing facilities that can be damaged or destroyed. Asia's agricultural landscape encompasses everything from intensive rice paddies and wheat fields to massive livestock operations and sophisticated food processing centres, creating a substantial economic base that, while productive, becomes vulnerable to catastrophic losses during extreme weather events.

While absolute loss amounts provide important insights into the scale of agricultural disasters, they can mask the true severity of impact on regional economies and populations. The most revealing analysis emerges when loss amounts are considered as a percentage of total agricultural GDP, unveiling a dramatically different narrative about vulnerability and resilience across regions (see FIGURE 10). High percentage losses indicate limited economic resilience and adaptive capacity to disaster shocks. For example, regions with developing and least developed countries show particularly acute vulnerability, where even moderate disaster events can devastate agricultural economies.

Despite experiencing lower absolute losses, Africa suffers the most severe relative economic impact at 7.4 percent of agricultural GDP – a number that represents a devastating impact on economies where agriculture often serves as the primary source of employment and economic activity. This percentage translates to significant disruptions in food security, rural livelihoods and overall economic stability across the continent. The Americas follow with 5.2 percent of agricultural GDP lost to disasters, reflecting the substantial impact on both developed and developing economies within the region, from the drought-affected agricultural zones of Brazil and Argentina to the hurricane-impacted farming communities of the Caribbean and Central America.

Oceania's 4.2 percent loss relative to agricultural GDP demonstrates how even a geographically smaller region can experience proportionally significant impacts, particularly given the concentration of agricultural activity in specific areas and the region's exposure to extreme weather events such as prolonged droughts and intense bushfires. Europe's 3.6 percent relative impact, while lower than other regions, still represents substantial economic disruption across diverse agricultural systems, from the Mediterranean's fruit and vegetable production to northern Europe's grain and dairy sectors.

At a subregional level, Western Africa emerges as the most vulnerable subregion with 13.4 percent agricultural GDP losses, a figure that represents an extraordinarily severe economic burden reflecting the subregion's acute exposure to climate-related disasters and limited adaptive capacity (see FIGURE 11). Southern Africa follows with 7.6 percent agricultural GDP losses, while Eastern Africa experiences 5.8 percent losses, creating a clear pattern of heightened vulnerability across the African continent that demonstrates how geographic, climatic and socioeconomic factors converge to create disproportionate disaster impacts. This continental pattern reflects shared challenges, including heavy reliance on agriculture for employment and economic stability, widespread dependence on rain-fed farming systems, and limited financial resources for disaster risk reduction and climate adaptation measures. The gradient of vulnerability across African subregions also reflects varying degrees of exposure to specific climate hazards, from the Sahel's vulnerability to drought and desertification to Southern Africa's exposure to cyclones and irregular rainfall patterns.

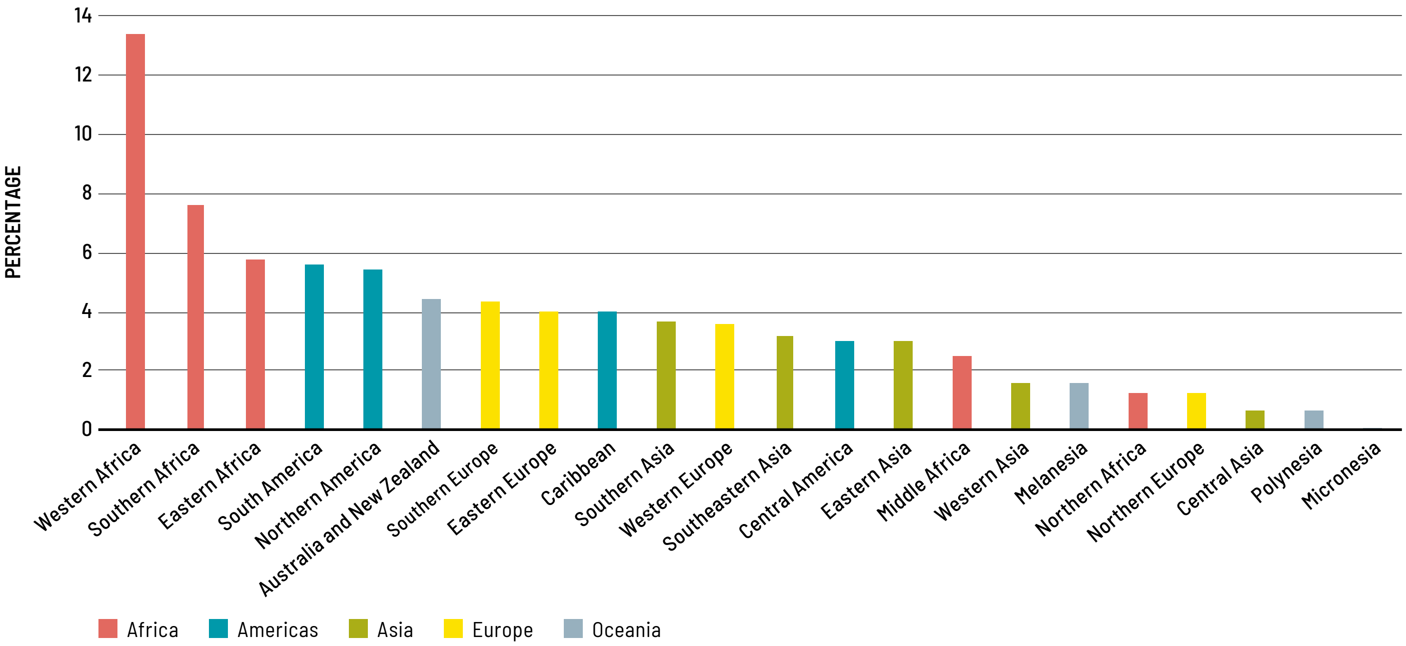
In the Americas, South America (5.6 percent) and Northern America (5.4 percent) show remarkably similar vulnerability levels, a convergence that reveals how vastly different economic structures, technological capabilities and disaster preparedness systems can result in comparable relative impacts. This similarity is particularly striking given the substantial differences in agricultural infrastructure, with North America featuring advanced irrigation systems, sophisticated early warning networks and comprehensive crop insurance programmes, while South America encompasses a broader range of agricultural systems from technologically advanced operations to traditional farming practices.

European subregions demonstrate relatively lower – yet still significant – impacts, with amounts that, although more moderate than in other global regions, nevertheless reflect substantial economic disruption across the continent's diverse agricultural landscape. The lower relative impact in Europe reflects the region's advanced agricultural infrastructure, sophisticated disaster preparedness systems, comprehensive early-warning networks and robust insurance mechanisms that provide greater resilience against climate-related shocks. However, even these technological advantages and institutional frameworks cannot entirely mitigate the increasing frequency and intensity of extreme weather events, with recent years witnessing significant agricultural losses from heat waves, droughts, floods and storms that have affected the region.

Disaggregating losses by country income groups reveals that lower-middle-income countries face absolute agricultural losses of USD 1.27 trillion (see FIGURE 12A). This amount represents the largest share of global losses due to disasters among all income categories, underscoring the concentration of vulnerable agricultural assets in countries that occupy the middle tier of global economic development. These nations

FIGURE 11

TOTAL AGRICULTURAL LOSSES AS A SHARE OF AGRICULTURAL GROSS DOMESTIC PRODUCT BY SUBREGION, 1991–2023



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig11

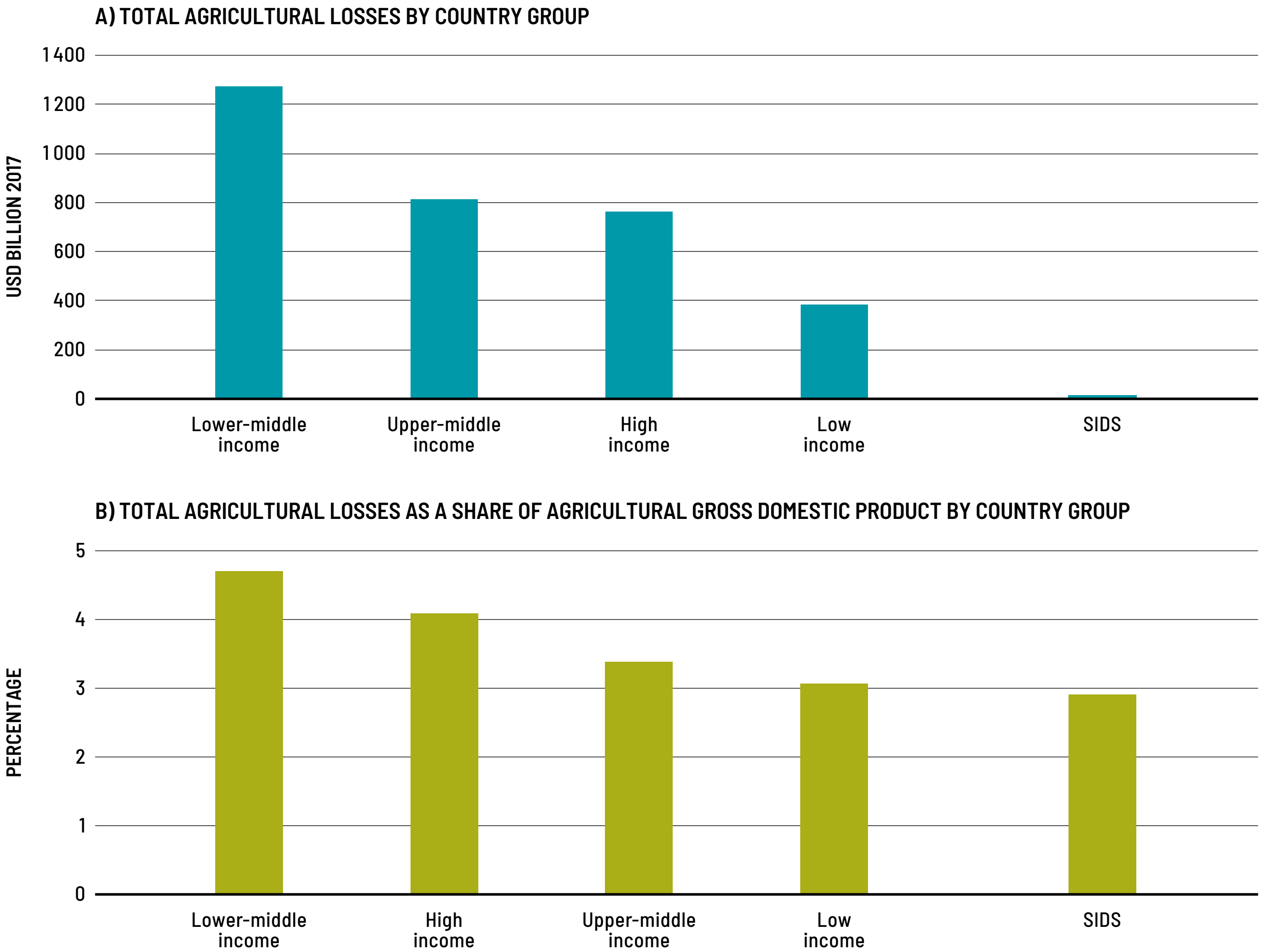
typically possess significant agricultural sectors that contribute substantially to their national economies while simultaneously lacking the advanced technological infrastructure and financial resources necessary to adequately protect these assets from increasingly frequent and severe extreme weather events.

Upper-middle-income countries follow with USD 813 billion in losses, while high-income countries experience USD 766 billion in damages, creating a clear pattern that demonstrates how absolute losses tend to correlate with the scale and value of agricultural production systems rather than simply with economic development levels. The proximity of losses between upper-middle-income and high-income countries suggests that as economies develop and agricultural systems become more intensive and valuable, the potential for substantial absolute losses increases correspondingly, even when protective infrastructure and disaster preparedness capabilities are enhanced.

Low-income countries (USD 386 billion) and Small Island Developing States (SIDS) (16 billion), while showing lower absolute losses, face severe relative impacts given their limited economic base, highlighting the critical distinction between the scale of damage and the capacity to absorb and recover from such losses. These lower absolute figures mask the profound vulnerability of these economies, where agricultural disasters can have catastrophic

FIGURE 12

ESTIMATED AGRICULTURAL LOSSES BY COUNTRY CATEGORY, 1991–2023



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig12

effects on national economic stability, food security and development prospects, despite representing smaller dollar amounts in global terms.

This pattern becomes more evident when losses are assessed as a percentage of agricultural GDP, revealing a dramatically different narrative about economic vulnerability and resilience capacity (see FIGURE 12B). Here, lower-middle-income countries suffer the highest relative agricultural losses at 4.7 percent of agricultural GDP, a proportion that represents a significant setback to economies where agriculture often serves as a primary engine of economic growth and employment. This percentage reflects the critical vulnerability gap that characterizes these nations, where substantial agricultural production occurs without adequate protective infrastructure, early-warning systems or financial mechanisms to mitigate disaster impacts.

High-income countries follow, with 4 percent of agricultural GDP lost to disasters – a figure that, while substantial, occurs within the context of more diversified economies and sophisticated disaster management systems. Upper-middle-income countries experience 3.4 percent agricultural GDP losses, while low-income countries face 3 percent losses, creating a pattern that reveals how relative vulnerability does not necessarily decrease linearly with economic development. SIDS face nearly 3 percent agricultural GDP losses despite their small absolute contributions – a proportion that represents severe economic disruption for small island economies, where agricultural production, while limited in scale, plays a crucial role in food security and local economic stability.

The high relative impact on lower-middle-income countries indicates a critical vulnerability gap, where countries have accumulated a larger amount of exposed agricultural resources and infrastructure but lack the advanced disaster resilience systems, comprehensive insurance mechanisms and financial capacity for rapid recovery that characterize high-income nations. These countries often find themselves in a precarious position where their agricultural sectors have expanded and intensified to support growing populations and economic development yet remain highly vulnerable to climate-related shocks due to insufficient investment in protective infrastructure, limited access to climate-resilient technologies and inadequate disaster preparedness institutions.

Despite their technological advantages, comprehensive early-warning systems and sophisticated disaster management capabilities, high-income countries still face significant losses due to intensive, high-value agricultural systems that remain inherently vulnerable to extreme weather events. The 4 percent agricultural GDP impact in these countries reflects the reality that even advanced agricultural technologies and infrastructure cannot entirely eliminate vulnerability to increasingly severe climate-related disasters, particularly when extreme weather events exceed the design parameters of existing protective systems.

SIDS exhibit disproportionately high impacts relative to their size (USD 16 billion), underscoring their extreme vulnerability to sea-level rise, storms and climate variability that can devastate entire agricultural sectors within a matter of hours or days. These nations face unique challenges, including limited land area for agricultural diversification, high exposure to coastal flooding and storm surge, dependence on imported agricultural inputs and minimal capacity for post-disaster recovery. This makes them among the most vulnerable populations to climate-related agricultural disasters, despite their small contribution to global agricultural production.

Losses by hazard type

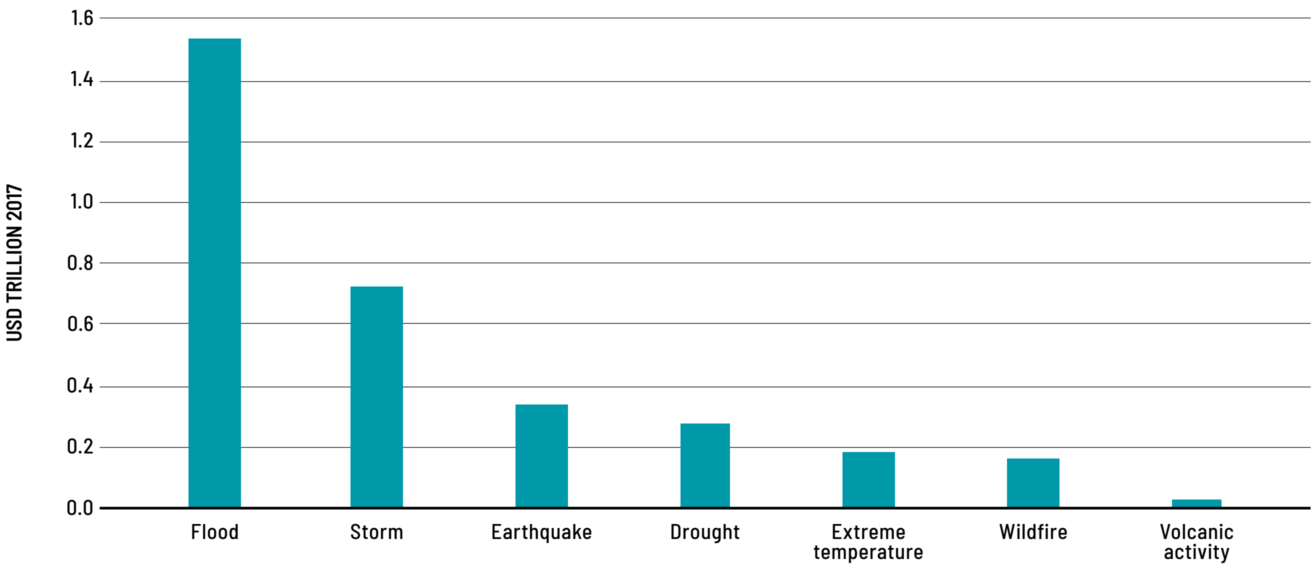
To assess how different types of natural hazard, such as droughts, floods, storms, or extreme temperature impact agricultural production, the analysis applies a resampling approach that creates a baseline of expected production in the absence of disasters. By systematically removing small portions of historical data and observing how loss estimates change, the method builds a reference point for what normal variation looks like. This allows for a fair comparison between disaster and non-disaster years. Losses are only attributed to a specific hazard type when they go beyond what would typically occur in a normal year, helping ensure that the impact of each disaster is measured accurately and not overestimated. This approach helps identify which hazard type cause significant damage in years with multiple disasters.

The results highlight the dominance of climate-related events on agriculture, especially hydrometeorological events such as floods and storms, which collectively account for the large majority of agricultural disaster losses (see FIGURE 13). They underscore the fundamental dependence of agricultural systems on water availability and the devastating impact that both water excess and water scarcity can have on crop production, livestock operations and agricultural infrastructure. Floods resulted in losses exceeding USD 1.5 trillion, representing the single most destructive hazard type for global agriculture and reflecting the widespread vulnerability of agricultural systems to water-related disasters. This massive figure encompasses damages from various flood types, including riverine flooding that can inundate vast agricultural areas for extended periods, flash floods that can destroy crops and agricultural infrastructure within hours and coastal flooding that threatens agricultural lands in low-lying areas.

Storms account for USD 720 billion in losses, a substantial amount that encompasses the impact of tropical cyclones, hurricanes, typhoons and severe thunderstorms on agricultural production systems worldwide. These extreme weather events combine multiple destructive forces, including high winds that can flatten crops and destroy agricultural structures, torrential rainfall that can cause flooding, and soil erosion and hail that can devastate entire harvests within minutes. The concentration of storm-related losses reflects the specific vulnerability of agriculture to these intense, short-duration events that can cause widespread destruction across multiple agricultural sectors simultaneously.

Earthquakes caused USD 336 billion in agricultural losses, representing significant damage despite being geological rather than climate-related events, and highlighting the vulnerability of agricultural infrastructure and livestock operations to seismic activity. While earthquakes may not directly destroy crops in the same manner as floods or storms, they can cause severe damage to agricultural processing facilities, storage infrastructure, irrigation systems and livestock housing, creating cascading effects throughout agricultural supply chains.

FIGURE 13
ECONOMIC LOSSES BY HAZARD TYPE, 1991–2023



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig13

Droughts resulted in USD 278 billion in documented losses, while extreme temperatures accounted for USD 186 billion, amounts that significantly underestimate the true impact of these slower-onset hazards on global agricultural production. Drought impacts on agriculture are particularly complex and far-reaching, affecting not only immediate crop yields but also soil health, groundwater resources and the long-term viability of agricultural operations. Similarly, extreme temperature events, including heat waves and unseasonal cold snaps, can cause substantial agricultural losses through crop stress, livestock mortality and disruption of critical agricultural processes.

Wildfires contributed USD 165 billion in losses, reflecting the growing threat that these events pose to agriculture, particularly in regions where agricultural lands interface with fire-prone natural vegetation. Volcanic activity resulted in USD 24 billion in agricultural losses, representing the smallest category but still reflecting significant regional impacts when eruptions occur in agricultural areas.

It is important to note that the amounts attributed to droughts and extreme temperatures are likely to be much higher, potentially representing a substantial underestimation of the real economic impact of these hazard types on global agricultural production. These two slower-onset hazard types are underreported in the EM-DAT database by a wide margin, which introduces a negative bias in the dataset and skews our understanding of the relative importance of different disaster types. The underreporting of drought and extreme temperature events occurs because these hazards typically develop gradually over extended periods, making it difficult to establish clear onset and termination dates, and their impacts may be distributed across multiple seasons or years, complicating efforts to quantify total losses. Additionally, the diffuse nature of these impacts makes them less likely to trigger formal disaster declarations or comprehensive damage assessments compared to sudden-onset events like floods or storms.

This breakdown of losses by hazard type differs significantly from that derived from PDNA data, as PDNAs are conducted only for select, major disasters that trigger international assistance or require comprehensive recovery planning. This constrains the reliability and representativeness of PDNA data, and creates a bias towards sudden-onset, high-impact events, while potentially overlooking the cumulative effects of more frequent, lower-intensity disasters. This methodological difference reflects limitations in the coverage of data from PDNAs and highlights the challenges in developing comprehensive assessments of agricultural disaster losses. It also underscores the importance of using multiple data sources and developing standardized analytical approaches to understand the full scope of agricultural vulnerability to natural hazards.

FOOD SECURITY AND NUTRITIONAL DIMENSIONS OF AGRICULTURAL DISASTER IMPACTS

Beyond direct economic losses, disasters can significantly impact the availability of nutrients in the food supply, with implications that extend far beyond immediate production statistics. Food security, nutrient intake, public health and long-term human development are all potentially affected. Understanding these nutritional dimensions is crucial for developing comprehensive response strategies that address not only agricultural recovery but also the broader health and well-being consequences of agricultural disasters for affected populations.

The nutritional impacts of disasters affecting agriculture operate through multiple pathways that affect food availability, access, utilization and stability in ways that can persist long after production systems are restored. Disasters may destroy crops that provide essential nutrients, disrupt food processing and preservation systems or force households to adopt dietary strategies that prioritize energy sufficiency rather than a healthy diet. These impacts may be particularly severe for populations at greater risk of malnutrition, including children, pregnant and lactating women, and elderly individuals who have specific nutritional requirements and limited capacity to adapt to dietary changes.

Disasters such as floods, storms or pest infestations can lead to lower dietary quality and increased risk of nutrient deficiencies among affected individuals through multiple mechanisms. These include the destruction of nutrient-rich crops, loss of livestock, contamination of food supplies, disruption of food processing and preservation systems, and reduced availability and access to diverse foods due to market disruptions. For example, a study investigating food security in Afghanistan found that exposure to flooding for one year reduced daily energy intake by an estimated 60 kilocalories per day while increasing the probability of iron, vitamin A and vitamin C deficiency by 11, 12 and 27 percentage points, respectively.[79]

Disasters can also disrupt access to nutritious foods, potentially forcing households to adopt quantity-over-quality approaches that emphasize staple foods over nutritious options, such as fruits and vegetables, which provide essential micronutrients.[80] This dietary shift may occur not only due to reduced production or availability of nutritious foods but also because of increased prices, disrupted market access or reduced household income following disasters that affect purchasing power for higher-value nutritious foods.

For example, grain production in the United States of America was severely disrupted due to a drought in 2012. This event had a significant impact on global markets as the United States of America is the world's largest exporter of major grain and oilseed crops. From 2008 to 2010, 39 percent of global maize was produced in the country, and it accounted for 49 percent of total global exports for the commodity. Due to the drought, maize prices increased by 53 percent compared to an already historically high five-year average price, and by 146 percent relative to the 2000–2009 average. This had widespread negative effects, particularly in developing countries where food costs make up a larger portion of household expenditures, and exacerbated food insecurity at the global level.[81]

Repeated disasters can lead to micronutrient deficiencies and chronic malnutrition, which undermine long-term growth and development and economic productivity, while increasing vulnerability to future shocks. The effects of nutritional deficiencies resulting from disasters can have long-term consequences that extend well beyond the immediate disaster period, particularly for children, whose physical and cognitive development may be permanently affected by malnutrition during critical growth periods. Severe nutritional deficiencies can make people increasingly vulnerable to disease while reducing productivity and learning capacity in ways that perpetuate poverty and vulnerability to future disasters.

To assess the potential nutritional impact of disasters, food composition data[82] were used to convert estimated agricultural production losses into nutrient losses for nine vitamins and minerals, as well as energy losses, providing insights into how disasters affect not only the quantity of food produced but also the availability of nutrients in the food supply. The analysis examined calcium, iron, zinc, vitamin A, thiamin, riboflavin, vitamin C, magnesium and phosphorus, using population estimates to calculate the average daily nutrient loss per person per day. The results were expressed as a percentage of adult nutrient requirements based on the daily estimated average requirement (EAR)[a] for each nutrient.[83,84,85]

a The estimated average requirement is the daily nutrient intake estimated to meet the requirements of 50 percent of healthy individuals in a given population group. EARs are conventionally used to assess the adequacy of nutrient intakes at the population level and to derive probabilistic estimates of nutrient inadequacy. For energy, estimated energy requirements (EERs) were calculated based on the median global population age in 2021 (30 years), average height (1.7 m for men and 1.6 m for women), and calculated weight (63.6 kg for men and 56.3 kg for women), using a conservative recommended body mass index (BMI) of 22 kg/m^2. An active physical activity level (PAL) coefficient was applied (1.25 for men and 1.27 for women). Resulting energy requirements used in the estimation of daily losses were 2 500 kcal/day for men and 2 000 kcal/day for women. Although EERs can be estimated across four physical activity levels, the active PAL is recommended to maintain health. Energy requirements are thus defined as the amount of energy an individual must consume to sustain a stable body weight within a healthy BMI range (18.5–25 kg/m^2), while maintaining adequate levels of physical activity.[86]

This approach provides quantitative estimates of how disasters in agriculture may impact nutrient availability in agrifood systems, while highlighting specific nutrients that are particularly vulnerable to different types of disasters. The analysis highlights how different crops and livestock products contribute distinct nutrients to human diets, indicating that disasters affecting specific agricultural subsectors may have distinct nutritional consequences that necessitate targeted intervention strategies.

It is important to note that food production, rather than actual consumption, is considered in this analysis, recognizing that the relationship between food production and actual consumption is mediated by multiple factors, including food distribution systems, market access and availability, purchasing power, consumer choice and dietary preferences, all of which may be affected by disasters. Food distribution among different population groups was not accounted for in this analysis, meaning that average food production was used as the basis for the calculations rather than examining how disasters might differentially affect different demographic groups.

Additionally, production losses for fish and aquatic foods were not included in this analysis, which may have underestimated the potential impact of disasters on nutrient supply by excluding this important source of nutrients, including high-quality protein, omega-3 fatty acids, and various vitamins and minerals that are particularly important. Fish and aquatic foods often provide crucial nutrition for coastal and inland fishing communities, and their exclusion from nutritional impact assessments represents a significant gap in understanding the full nutritional consequences of disasters.

FIGURE 14 shows that, globally, estimated production losses from disasters in the crops and livestock subsectors have averaged approximately 320 kilocalories per person per day over the past 33 years. This amount represents roughly 13 to 16 percent of the average daily energy needs for men and women, respectively (see FIGURE 17 and FIGURE 18). The decrease in available energy is equivalent to the requirements of approximately 1.05 billion people annually over the last three decades.

Grain-based foods are fundamental dietary staples in many regions worldwide, serving as primary sources of energy and essential nutrients. Consequently, reductions in cereal production are the most significant contributors to losses in energy and essential micronutrients such as iron, zinc, magnesium, phosphorus, thiamin and riboflavin (FIGURE 15). Vegetables are the leading factor for vitamin A losses, emphasizing their importance as key providers of this nutrient, which is critical for vision, immune system function and overall health.[87] Losses of vitamin C in diets are largely due to the absence of fruits and nuts, as well as vegetables, roots and tubers. Similarly, insufficient consumption of milk and eggs results in losses of calcium, vitamin A and riboflavin.

When compared to standard dietary requirements, potentially important nutritional losses are evident for iron, phosphorus, magnesium and thiamin (see FIGURE 16). The loss percentages generally display similar trends by sex across most nutrient categories; however, notable differences emerge in the cases of iron, magnesium and zinc. In interpreting the findings, it is important to note that a high value for the percentage of EAR can either be driven by high losses of foods containing this nutrient, a low requirement or both. »

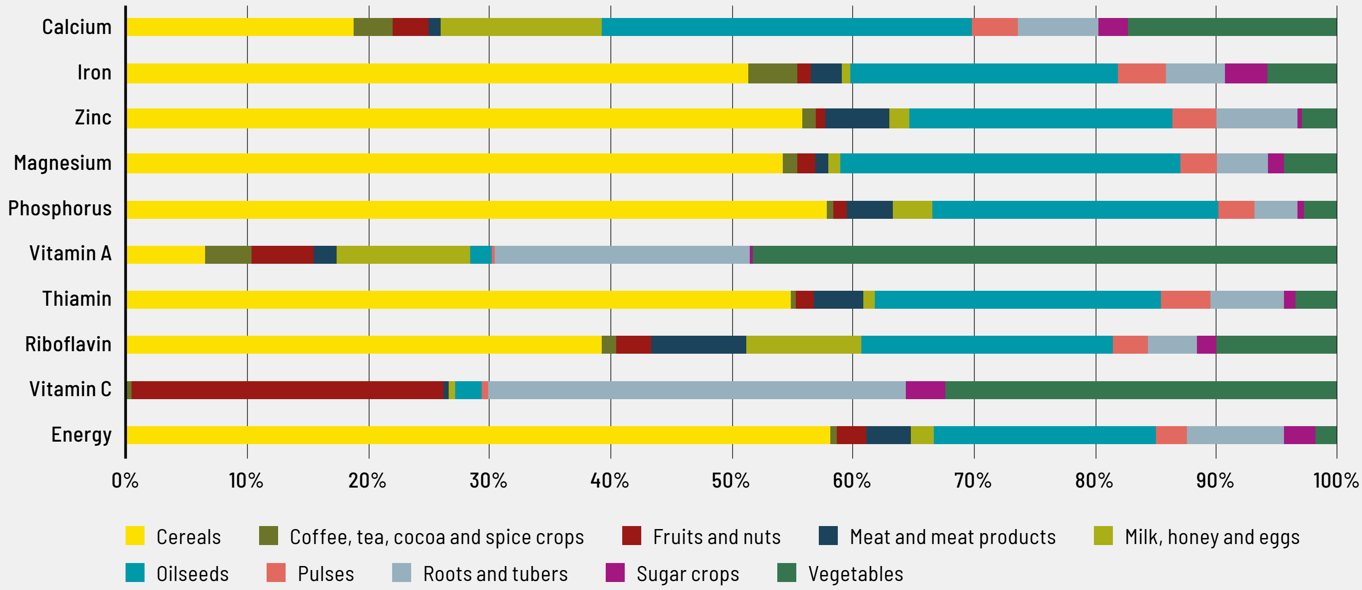
FIGURE 14
TOTAL ESTIMATED DAILY LOSSES OF ENERGY AND NUTRIENTS PER PERSON PER DAY, 1991–2023

Vitamin C	15 mg
Riboflavin	0.15 mg
Thiamin	0.36 mg
Vitamin A	39 retinol activity equivalents mcg
Zinc	2.29 mg
Phosphorus	274 mg
Magnesium	111 mg
Iron	3.6 mg
Calcium	66 mg
Energy	320 kcal

Note: mg = milligram, mcg = microgram, kcal = kilocalories.
Source: Authors' own elaboration based on FAO data.

FIGURE 15

TOTAL ESTIMATED DAILY LOSSES OF ENERGY AND NUTRIENTS PER PERSON PER DAY BY FOOD GROUP, 1991–2023

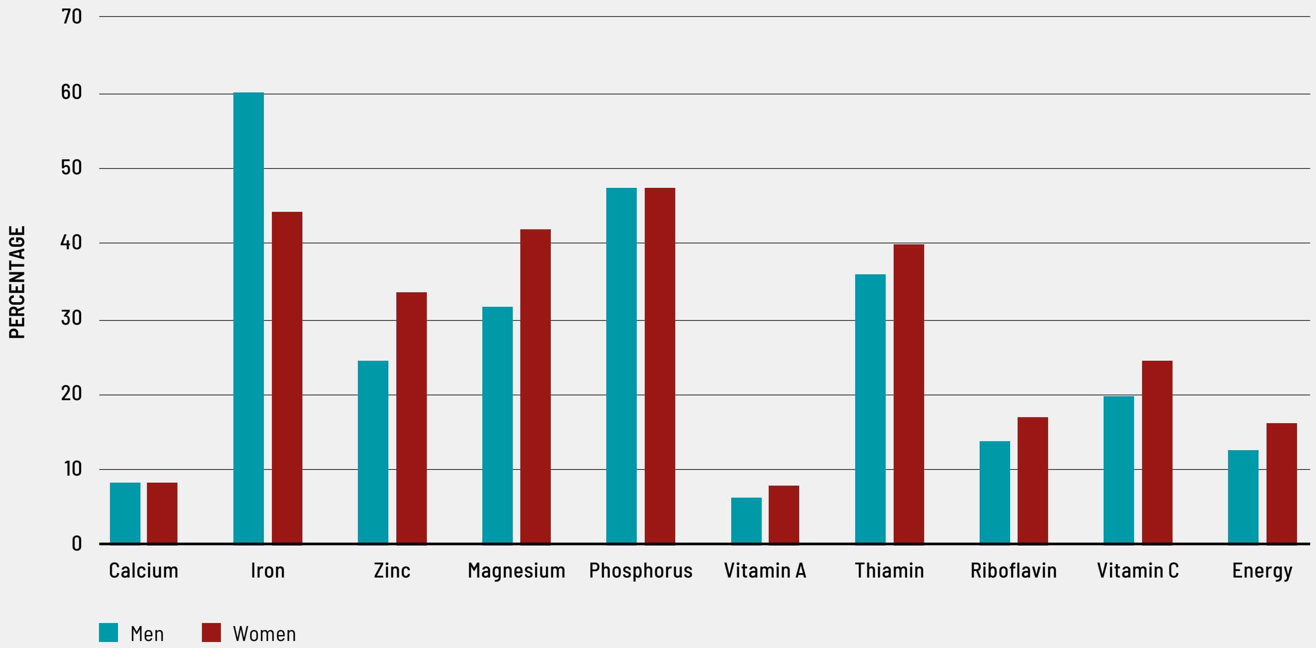


Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig15

FIGURE 16

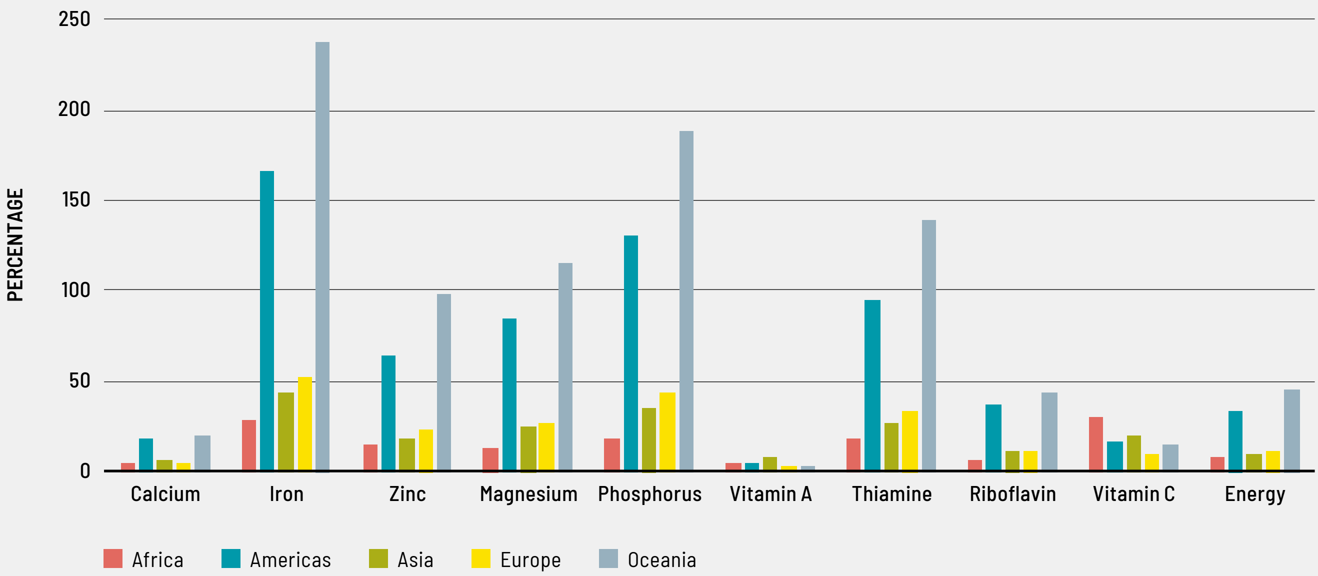
ESTIMATED DAILY LOSSES OF ENERGY AND NUTRIENTS AS A SHARE OF HUMAN REQUIREMENTS, 1991–2023



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig16

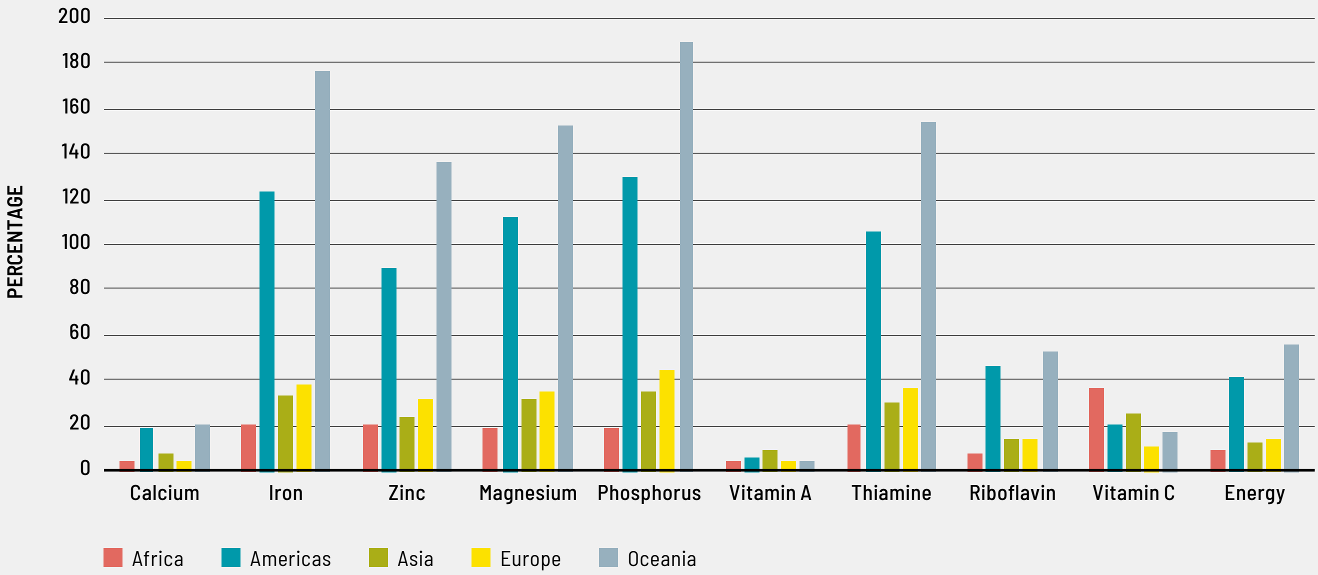
FIGURE 17
ESTIMATED DAILY LOSSES OF ENERGY AND NUTRIENTS AS A SHARE OF HUMAN REQUIREMENTS FOR MEN BY REGION, 1991–2023



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig17

FIGURE 18
ESTIMATED DAILY LOSSES OF ENERGY AND NUTRIENTS AS A SHARE OF HUMAN REQUIREMENTS FOR WOMEN BY REGION, 1991–2023



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig18

» Therefore, a high percentage EAR should not be interpreted as a greater impact of disasters on the supply of this nutrient.

As shown in FIGURE 17 and FIGURE 18, the projected losses, measured as percentages of EAR, are highest in Oceania, exceeding 100 percent of EAR for both men and women for iron, magnesium, phosphorus, thiamin, and, for women specifically, zinc. The Americas rank second in these projected losses. These figures reflect reductions in nutrient supply due to lower production levels, not changes in actual dietary consumption or intake patterns. Although the total nutrient losses in Oceania are smaller compared to other regions, the comparatively small population and significant food export activities result in higher per capita daily nutrient losses, contributing to high losses when expressed as a percentage of EAR. For instance, the estimated per capita daily iron loss in Oceania is 14.2 mg, corresponding to 236.8 percent of the EAR for men (6 mg/day) and 175.4 percent for women (8.1 mg/day).

This analysis demonstrates the importance of considering the nutritional dimension in disaster impact assessment and response planning. Policies and programmes designed to prevent and mitigate disasters and protect nutritious foods can significantly contribute to achieving global goals of ending malnutrition in all its forms, while building more resilient agrifood systems that can maintain nutritional adequacy and diversity even under stress. The findings also highlight the need for enhanced nutritional surveillance and assessment capabilities that can enable timely and targeted interventions, especially for the most vulnerable populations.

2.4 FISHERIES AND AQUACULTURE AS A SPECIAL CASE

Fisheries and aquaculture represent a unique and particularly complex case within agricultural disaster impact assessment, facing distinct challenges that reflect their direct dependence on natural ecosystems, location in exposed and vulnerable coastal and riparian areas, and the inherent difficulty of monitoring and managing aquatic resources compared to terrestrial agricultural systems. These sectors provide food security, nutrition and livelihoods for some of the world's most vulnerable, marginalized and disadvantaged communities, while making significant contributions to global food production and international trade.

The importance of fisheries and aquaculture for global food security cannot be overstated, with these sectors providing animal protein, essential micronutrients and livelihoods for hundreds of millions of people worldwide. As of 2022, 61.8 million people were engaged in primary fisheries and aquaculture production, mainly in small-scale operations that form the backbone of rural economies in many developing countries.[88] Subsistence and secondary sector workers, along with their dependents, are part of the estimated 500 million people who rely on small-scale fisheries for their livelihoods. This total includes 53 million engaged in subsistence fishing, 45 percent of whom are women.[82]

The vulnerability of fisheries and aquaculture to disasters reflects their exposure to a wide range of hazards that can affect both the natural resource base and the human systems that depend on aquatic resources. Whether sudden-onset events, such as cyclones, tsunamis, and floods, or slow-onset threats, including sea-level rise, ocean acidification and shifts in sea surface temperature, disasters can impact fish stocks, destroy critical fisheries assets and infrastructure, and disrupt the livelihoods of millions who depend on fishing for their survival and economic well-being.

Small-scale fishers, especially those in low-income and fragile regions, face heightened risks from disasters, as they often lack access to early-warning systems and the ability to prepare, including the use of anticipatory action strategies, insurance schemes or social safety nets that could help them cope with disaster impacts. Beyond the immediate physical damages, losses and potential fatalities, disasters can have long-term consequences for food security and nutrition, environmental preservation, economic stability, social stability and community resilience, which may persist for years or decades.

Fisheries are vulnerable to single, simultaneous, compounding and cascading disaster impacts, each posing unique challenges that require different response strategies and recovery approaches. A single disaster, such as a tropical cyclone or flood, can immediately destroy fishing assets, disrupt fishing operations, damage infrastructure, degrade fish stocks, and disrupt livelihoods in ways that may take months or years to recover. Simultaneous events, such as consecutive cyclones, can compound damage, leaving little time for an effective and efficient response and recovery, while prolonging social and economic hardship for affected communities.

The intricate relationships between extreme climate events and fisheries are not fully understood. However, evidence suggests that rising variability in environmental factors, such as temperature, precipitation and wind patterns, influences fish growth, development, reproduction, mortality, distribution and migration, while also indirectly affecting the productivity, structure and composition of fish ecosystems. For example, the 2023 El Niño conditions resulted in a 50 percent reduction in the landings of the world's largest single-species fishery, the Peruvian anchoveta, compared to 2022, impacting local livelihoods, national export revenues, and indirectly affecting sectors that depend on fishmeal and fish oil.[82]

While rapid restoration of fisheries activities can quickly provide nutritious foods and employment following disasters, making it an attractive intervention strategy, this reactive focus may miss opportunities for more proactive and cost-effective investments in prevention and preparedness that could reduce future disaster impacts. Compared to other sectors, the potential for rapid recovery in fisheries and aquaculture can provide immediate benefits for affected communities; however, long-term sustainability requires more comprehensive approaches that address underlying vulnerabilities and build resilience.

Assessment challenges in fisheries and aquaculture are particularly substantial due to several factors that distinguish this sector from crop and livestock agriculture, creating unique difficulties for systematic impact monitoring and evaluation. The sector is largely made up of small-scale fishers who are often not formally registered, and whose vessels and other assets are frequently undocumented in official records – resulting in limited baseline data for assessing post-disaster damages and losses. The frequent lack of comprehensive data on fish catches, fishing effort and economic value of fishing activities represents another significant challenge for quantifying disaster impacts using standard economic assessment methodologies. Many fishers and fish workers operate in the informal economy with limited documentation of their activities, assets or income, making it difficult to establish pre-disaster baselines or measure post-disaster changes using conventional assessment approaches.

Fishing communities are often located in remote coastal or riverine areas that become difficult or impossible to access when critical infrastructure is damaged or disasters disrupt communication systems. When post-disaster needs assessments (PDNAs) or rapid damage and needs assessments are undertaken, these areas may be too difficult or costly to reach for comprehensive evaluation, leading to the systematic underrepresentation of impacts on fisheries in disaster assessments.

The impacts of disasters on fisheries are complex and ecosystem-based, involving changes in fish behaviour, habitat degradation, water quality deterioration and ecological relationships that are not easily observed without specialized monitoring equipment and expertise. Unlike terrestrial agriculture, where crop damage is readily visible, fisheries impacts often involve underwater or offshore changes that require specialized assessment techniques and may not become apparent until fishing activities resume.

These assessment challenges extend to downstream segments of the fisheries value chain, including fish markets and cold chain systems that are critical for maintaining product quality and accessing profitable markets. Disasters frequently disrupt power supplies, transportation routes and storage infrastructure, resulting in immediate losses and the wastage of perishable fish products, while creating long-term disruptions in supply chain continuity that affect market access and profitability for extended periods.

As a result, post-disaster assessment and response in fisheries often overlook the sector, despite its significant importance for food security and livelihoods, resulting in limited support for recovery and rehabilitation that may leave affected communities struggling to restore their livelihoods. In this regard, the forestry and fisheries subsectors suffer from a lack of comprehensive information on their production, assets, activities and livelihoods, leading to frequent exclusion from post-disaster impact evaluations and needs assessments.[89]

To address these limitations, FAO has developed specialized guidelines and training programmes designed to enhance the capacity of governments and other stakeholders to conduct comprehensive assessments of the impacts of fisheries and aquaculture disasters.[90] The Fisheries and Aquaculture Response to Emergency (FARE) training was delivered in four Caribbean SIDS, as well as Nicaragua, in 2024. In 2025, FARE was delivered in Belize, and further training is planned for Africa, Asia, and Latin America to expand the number of people trained in conducting assessments after disasters in the fisheries and aquaculture sector.

The training covers five main areas for assessment: fishing gear, vessels and engines; fisheries and aquaculture policy and management; landing sites, harbours and anchorages; aquaculture operations; post-harvest marketing and processing facilities; and environmental impacts. This comprehensive approach recognizes that disasters affect multiple components of the fisheries and aquaculture sector that require integrated assessment and response strategies. Key challenges identified through these training programmes include limited awareness and understanding of the fisheries and aquaculture sector among general disaster management personnel, the high costs associated with repairing or replacing fishing vessels and gear particularly for unregistered fishers or those lacking insurance, insufficient training across various institutional levels, and the absence of pre-established response plans to ensure timely and appropriate delivery of fishing equipment following disasters.

The integration of technological innovations, particularly drone technology combined with GIS remote sensing, blockchain, AI using ML algorithms, cloud computing, crowdsourcing and IoT sensors, offers promising solutions for addressing assessment challenges in fisheries while enhancing preparedness and response capabilities. Drones equipped with high-resolution cameras, sensors and technology can access remote areas and obtain near-real-time, high-resolution, spatially referenced aerial data of affected areas, enabling rapid assessment of damage to fisheries infrastructure and marine ecosystems.

These technologies can facilitate the mapping and monitoring of fish species and their habitats, such as mangroves and coral reefs, to assess biophysical degradation caused by disasters. This assessment creates detailed maps, three-dimensional models and orthomosaics of areas vulnerable to disasters, including fishing ports, cold storage facilities and processing plants. Additionally, drones can identify damaged or blocked supply routes, facilitate faster recovery of transportation networks, and assist in gathering data on affected fisheries and aquaculture communities.

However, technological interventions must be coupled with strengthened institutional capacities, enabling policy frameworks, and targeted investments to be effective in enhancing fisheries disaster risk management. Without complementary investments in human capital development, institutional strengthening and policy reform, technological solutions alone cannot address the fundamental vulnerabilities that make fisheries communities susceptible to disaster impacts.

The experience of fisheries and aquaculture highlights broader lessons for agricultural disaster risk management – including the importance of sector-specific approaches that recognize unique vulnerabilities and characteristics; the need for improved data collection and monitoring systems capable of capturing complex impacts; and the value of integrating technological innovations with institutional capacity building and policy reform to develop comprehensive solutions that address both immediate response needs and long-term resilience.

Without enhanced data collection and strategic action, the sector will remain under-prioritized in disaster response frameworks, limiting its potential to contribute to recovery, resilience and sustainable development in disaster-prone areas while leaving millions of people dependent on fisheries vulnerable to future disasters. The following section presents a novel attempt to quantify the impacts of marine heatwaves on global fisheries, as a first step towards developing data tools and methodologies that can provide evidence on the different loss trajectories in this subsector.

Quantifying the impacts of marine heatwaves

MHWs can be described as prolonged and discrete events of abnormally warm water, characterized by their persistence, intensity, rate of change and geographic coverage. From a quantitative perspective, MHWs are events that persist for a minimum of five days, characterized by temperatures exceeding the 90th percentile based on a historical reference period of 30 years.[91] FIGURE 19 depicts the accumulated number of days under strong to extraordinary MHWs across the global ocean during the period 1982–2022, and separately for 2013–2022 to highlight the intensity of the most recent decade. The data are drawn from a database using the events classification developed by Hobday *et al.*[92]

Climate change is increasing the frequency and severity of large-scale MHWs.[93] The rise in sea temperature has led to a significant increase of over 82 percent in the occurrence of MHWs across the world ocean.[94,95] In a similar vein, the global count of days experiencing MHWs has risen during the 20th and early 21st centuries. On average, there has been a 50 percent increase in the number of MHWs days per year in the last three decades.[96]

MHWs have significant effects on ocean life. Mild events can sometimes enhance ocean chemistry and biology, but stronger ones may lead to a harmful buildup of organic matter and low oxygen levels. The response of ecosystems depends on the context.[97] Strong MHWs can alter the distribution and abundance of species, causing mass mortality and ecosystem disruptions.[98,99,100] Thermal stress can alter how fish grow, reproduce and behave, leading to population declines and shifts in marine communities throughout the water column.[101,102,103]

The impacts can thus include changes in fishing yields, deterioration in fish quality and shifts in fishing areas, as well as business-related impacts along the fish value chain, including higher expenses, less valuable alternative fisheries and decreased profitability. These can have significant implications on food security and livelihoods, especially in areas with limited nutritional options, such as low-income nations in Africa, Asia, Australasia and Central and South America.[104]

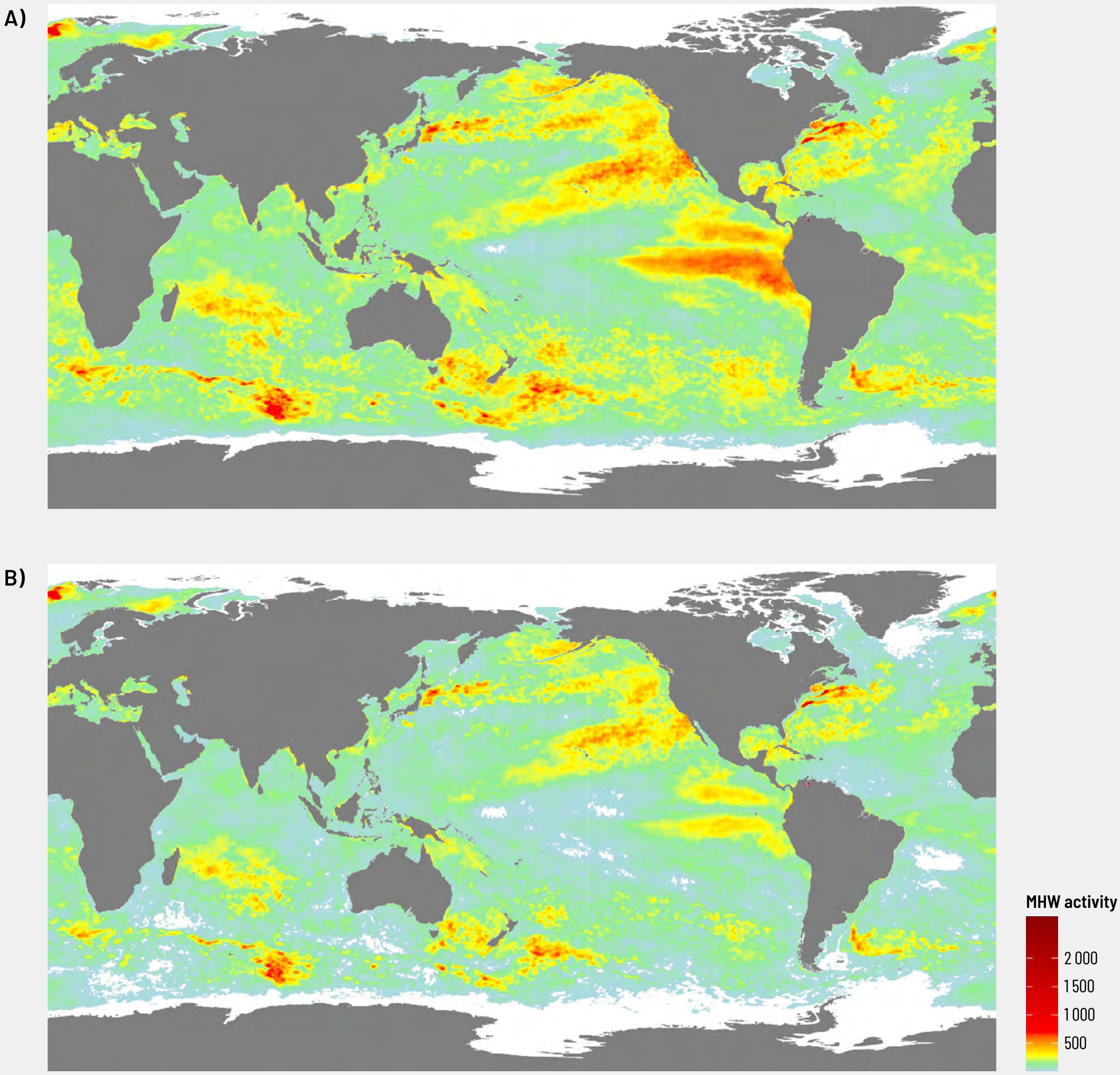
The following analysis of the global impacts of MHWs on marine fisheries was conducted at the spatial scale of exclusive economic zones, the highest resolution achievable based on FAO's global fisheries statistics. For the empirical analysis of the links between MHWs activity and marine fisheries, the study focused on a spatial scale that combines the exclusive economic zones (EEZs) and FAO's definition of Major Fishing Areas (MFAs). Because fisheries statistics are only available at the annual scale, the MHWs activity, which occurs at a timescale of days to months, was aggregated for each year to allow for comparison.

The investigation examined 2088 fisheries across 128 regions and 108 countries (production from countries fishing outside their EEZ was excluded), spanning a 37-year period from 1985 to 2022. The results demonstrate empirical evidence that MHWs resulted in an estimated production loss of over 5.6 million tonnes and impacted 15 percent of fisheries, predominantly concentrated in the last decade. The economic losses due to such production shortfalls amount to USD 6.6 billion, of which USD 3.9 billion occurred in the decade from 2013 to 2022. The results revealed no clear correlation between areas with higher MHW activity and the number or size of affected fisheries or losses. Instead, the proportion of affected fisheries remains relatively constant across regions, but areas with larger catches experienced a greater impact (FIGURE 20).

The most significant production losses were observed in the Northern Eastern Atlantic, »

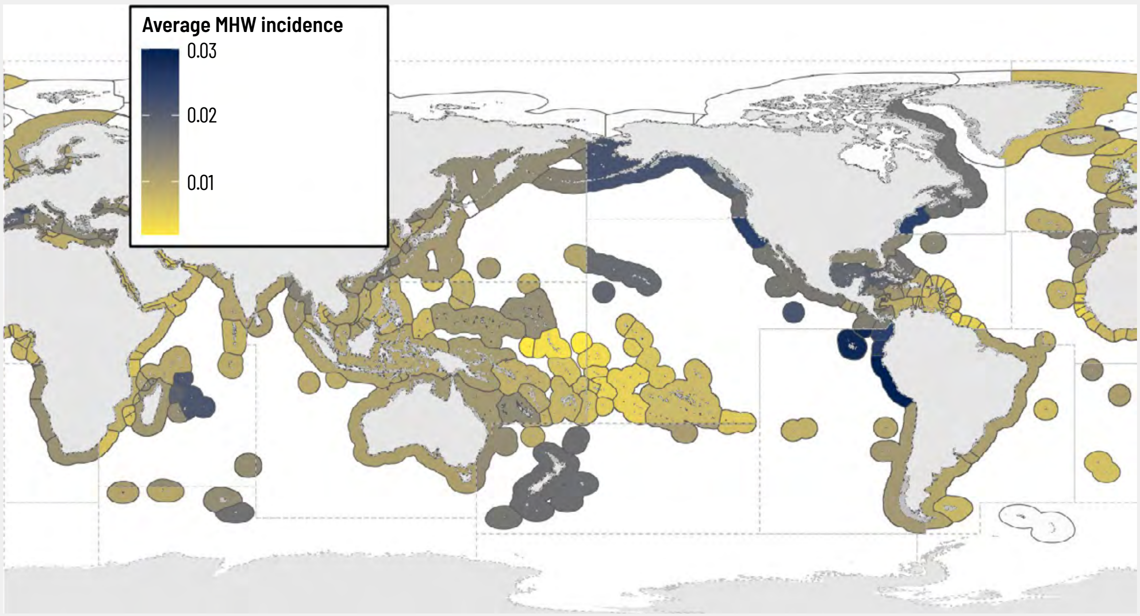
FIGURE 19

GLOBAL DISTRIBUTION OF ACCUMULATED STRONG TO EXTRAORDINARY MHW ACTIVITY DURING THE 1985–2022 (A) AND 2013–2022 (B) PERIODS

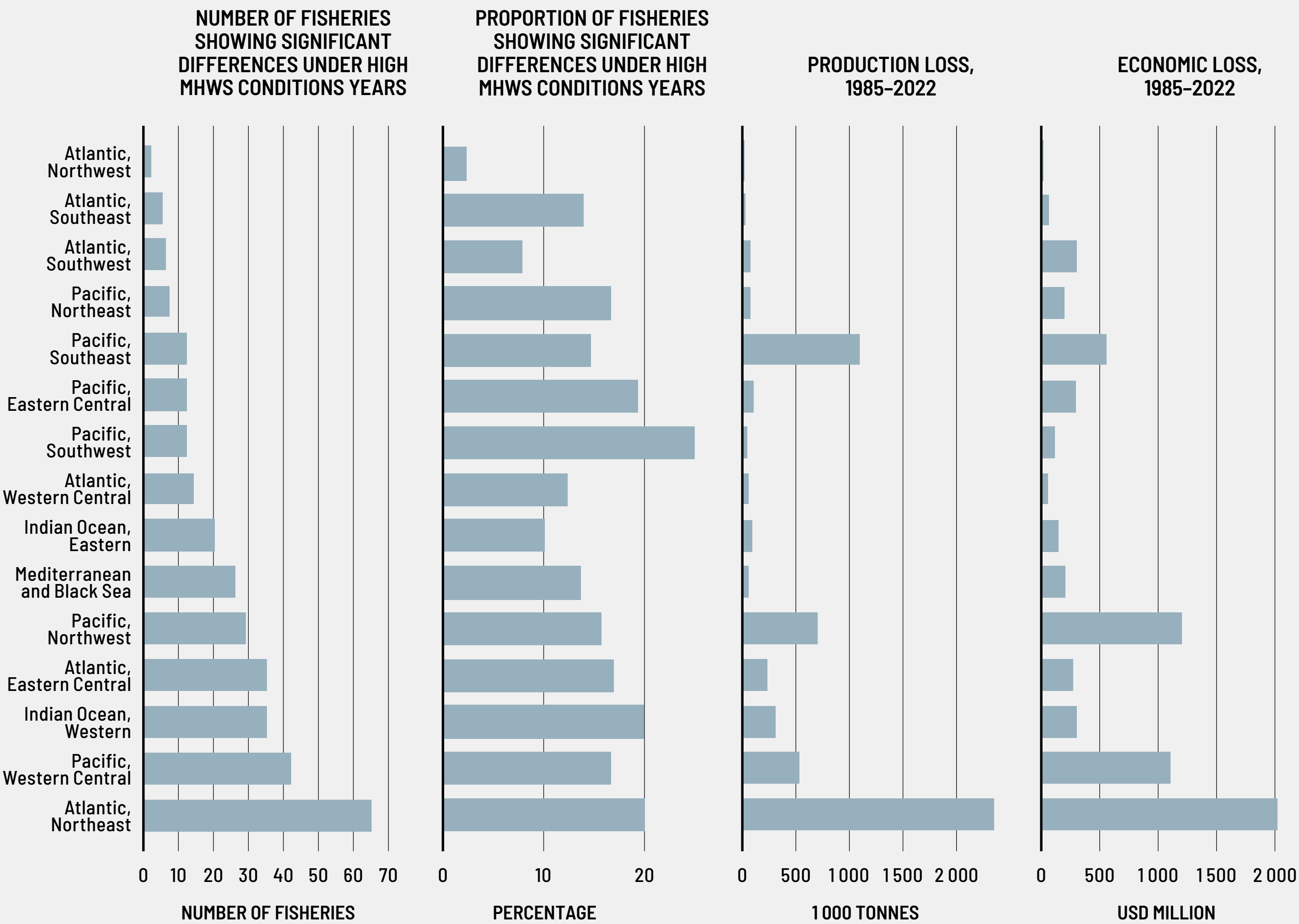


Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.
Source: Authors' own elaboration based on data from Hobday, A., CSIRO, Oliver, E., Sen Gupta, A., Benthuysen, J., Burrows, M., Donat, M., Holbrook, N., Moore, P., Thomsen, M., Wernberg, T. & Smale, D. 2018. *Categorizing and naming marine heatwaves*. Oceanography (Washington, D.C.), 31(2). https://doi.org/10.5670/oceanog.2018.205. Cambridge, UK, Cambridge University Press and the wider literature.

FIGURE 20
UPPER PANEL: AVERAGE MHWS INCIDENCE PER EZZ/MFA
LOWER PANEL: IMPACTS ON FISHERIES PER MFA



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.



Source: Authors' own elaboration.

https://doi.org/10.4060/cd7185en-fig20

» followed by the Southern Eastern Pacific, with somewhat lesser losses in the Western Central and southern regions of the Northern Western Pacific, as well as the western coast of India. At the national level, Norway, Denmark, Japan and China account for over half of the global impact, with Peru – one of the world's top fish producers – also significantly affected. Likewise, there is no clear pattern showing which species are more affected, as production and economic losses are more linked to the number of fisheries analysed than to species-specific traits. However, herrings, sardines and anchovies stand out, showing the most significant decline in production, despite ranking fourth in the number of cases examined. Over the past decade, MHW activity has increased, particularly in regions less influenced by El Niño–Southern Oscillation (ENSO) dynamics, such as the Northern Western Pacific, parts of the Western Central Atlantic, the Greenland Sea and areas of the Mediterranean.

Further research to assess the impacts of MHW on fish production is needed to improve the measurement of MHW activity, especially its spatial distribution and duration, and adopt a case-by-case approach to assess impacts, focusing on the physical mechanisms, fish population biology and regional climate signals for each MHW event. Enhanced spatial resolution, additional catch and pricing data and a better understanding of local physical processes will be crucial for this research.

Not all sensitive fisheries are the most vulnerable if they can adapt well. Early-warning systems and responsive management are crucial in mitigating risks associated with events like MHWs.[105] Proactive decisions, such as adjusting quotas or closing areas, can help protect ecosystems and enable fisheries to respond in real-time. Effective adaptive management depends on leadership, regulations, market dynamics and operational costs. Long-term resilience strategies include diversifying target species, integrating climate risks into policies, fostering international cooperation and offering economic support or insurance for affected communities.

As detailed in **Part 3** of this report, digital technologies transform risk management capabilities by offering unprecedented opportunities to enhance assessment methodologies and address longstanding measurement challenges. The integration of remote sensing, AI, mobile technologies, and advanced analytics offers potential solutions to many current limitations, while enabling more comprehensive, timely and cost-effective impact assessments. However, realizing this potential requires addressing fundamental gaps in conceptual frameworks, institutional capacity and data governance that currently limit the effectiveness of evaluations. ■

UNITED STATES OF AMERICA
Autonomous harvester working in a field.

PART 3

DIGITAL SOLUTIONS FOR DISASTER RISK REDUCTION IN AGRICULTURE – FROM INNOVATION TO IMPLEMENTATION

KEY MESSAGES

➔ **Digital technologies and tools are revolutionizing risk monitoring in agriculture**. Interoperable digital platforms, transform raw climate, soil, socioeconomic and hazard data into actionable intelligence. Advanced analytics powered by AI and ML now deliver integrated hyperlocal, real-time and actionable risk information.

➔ **Given their potential to reduce the risk and impact of disasters, digital solutions are critical for agrifood system resilience.** Data platforms bridge infrastructure gaps and allow for the timely and at-scale deployment of risk transfer mechanisms – for example, insurance or social protection. Advanced analytics help improve early warning systems and design anticipatory actions.

➔ **Digital solutions allow for a shift from a reactive response to proactive risk reduction and prevention.** Improved access to real-time and actionable intelligence strengthens the ability of policymakers and farmers to take risk-informed decisions.

➔ **A digital transformation requires a comprehensive enabling environment.** Digital transformation succeeds when innovation is matched with sustained investment in capacity development, institutional strengthening and enabling infrastructure. Coherent policy frameworks are essential to scale and sustain digital solutions, ensure alignment with local priorities, and create the conditions for long-term resilience building across agrifood systems.

➔ **Human-centred design dramatically improves adoption and impact.** Digital solutions are most effective when they are co-designed with the communities they are supposed to serve – for example, smallholder farmers. Evidence shows that human-centred approaches significantly boost adoption and ensure that the benefits of digital innovation reach those most vulnerable and exposed to disaster risks.

The structure of this part of the report follows a progression that mirrors the journey of digital transformation in agricultural disaster risk reduction. **Section 3.1** on digital technologies transforming agricultural risk management sets the foundational landscape by examining the current challenges facing agriculture and introducing the diverse array of digital tools now available. This section provides readers with a comprehensive understanding of how digital solutions are revolutionizing risk knowledge, monitoring systems and advisory services. By starting with the "what" – the technologies themselves and their immediate applications – the discussion is grounded in concrete examples and proven solutions to establish a solid knowledge base for subsequent sections.

Section 3.2, from early warning to resilient action, demonstrates how these digital tools translate into tangible outcomes for farmers and communities. This section bridges the gap between technology and impact, showing how early-warning systems enable anticipatory actions, how predictive analytics inform decision-making, and how digital innovations build long-term resilience through insurance, social protection and improved disaster preparedness, response and recovery. Finally, **Section 3.3** (Mainstreaming digital solutions at scale), addresses the critical question of implementation, examining the enabling conditions, policy frameworks, and human-centred approaches necessary to scale these solutions effectively. This progression from tools to action to scale reflects the real-world pathway of digital transformation, while also providing entry points for various stakeholders – whether they are seeking to understand available technologies, implement specific solutions or develop enabling environments for digital innovation in their contexts. ■

3.1. DIGITAL TECHNOLOGIES TRANSFORMING AGRICULTURAL RISK MANAGEMENT

THE LANDSCAPE OF DIGITAL DISASTER RISK REDUCTION IN AGRICULTURE

Agriculture faces unprecedented challenges from increasingly frequent and severe disasters, fundamentally reshaping how we must approach risk management in the sector. As discussed in **Part 2** of the report, the economic effects of localized disasters extend far beyond immediate production losses, cascading through global agrifood systems to affect prices, trade and food security far from the initial impact zone. The vulnerability of agricultural systems is further compounded by their exposure to multiple, often simultaneous hazards that can erase years of agricultural development progress and push entire populations into food insecurity.

The complex and interconnected nature of risk requires advanced analysis for production, interpretation, and communication of actionable information to support decision-making and implementation processes. The lack of timely, localized and actionable information remains a critical gap, especially in regions with limited infrastructure, logistical barriers and conflict situations. Data-driven risk information must be made available and accessible to both farmers and policymakers in formats that are tailored to their needs, ranging from farm-level decision-making to multilevel strategic planning and policy development that support sustainable agriculture.

Digital solutions can serve as a conduit for transferring knowledge to multiple stakeholders and policymakers, empowering them to act. However, for digital solutions to be effective, they must be affordable, accessible, available and capable of overcoming challenges for rural communities, such as the digital divide, unreliable electricity, and limited connectivity and access to the internet and mobile networks.

Farmers also face a range of challenges that include a lack of access to advisories and credits, high cost of inputs, exposure to natural and biological hazards, poor market linkages, limited access to technology and knowledge, and economic burden. These, in turn, affect the ability of farmers to be resilient in the face of disaster risk. Digital tools can help overcome some of these challenges and provide innovative solutions for improving access to advisory services and market linkages, and by facilitating access to credit and loans through traceable means.[106,107,108]

Facilitated by AI and ML, advanced analytical models have improved our understanding of risk through the integration of multiple types and scales of data (e.g. socioeconomic, farm registration, soil health, crop assessment, land use, metrological, hazard and climate data).[4,5] These high-quality data are woven into context-specific digital solutions for building the resilience of farmers and stakeholders, and their widespread use is key to the provision of actionable risk information to farmers and the improvement of agricultural practices.

The growth of new technologies also brings opportunities for extension and advisory services (EAS), bridging the information gap between different value chain actors, contributing to fair trade, market accessibility, and social and financial inclusion, and enhancing accessibility, delivery, transparency, scope, and impacts of information and services.[109] Key elements of digital technologies can provide hyperlocal and personalized agriculture EAS in terms of agrometeorological advisories, education, access to microfinance and insurance services, market prices, supply chain management, and pest and disease advisories, which are frequently bundled together by service providers.[110]

Location-specific, real-time and context-sensitive EAS help farmers tailor their agronomic practices based on weather patterns and market demands. The possibility to culturally and linguistically customize information ensures targeted messages that bridge key socioeconomic gaps in rural communities, and the use of simultaneous multichannel delivery of EAS through radio, television, mobile phone and the internet can help overcome accessibility challenges, including literacy.

Before examining how digital tools enable proactive responses to agricultural disasters, we must first understand what these technologies are and how they function. This section surveys the digital innovations currently reshaping agricultural risk management—from satellite monitoring systems and data platforms to mobile advisory services and predictive analytics. Each subsection demonstrates specific technological capabilities through working examples, building from basic data collection tools to more sophisticated analytical systems. This progressive exploration of existing technologies and their applications prepares the ground for **Section 3.2**'s examination of how these same tools drive anticipatory action and long-term resilience building.

DIGITAL TOOLS FOR RISK KNOWLEDGE AND MONITORING

Digital solutions enhance data collection, analysis and granularity. Gaining a better understanding of disaster risks and their trends depends on accessing granular, detailed data that provide insights into the multifaceted dimensions of hazards, such as likelihood, intensity, timing and effects. This process allows for the identification of risk patterns or trends, which inform planning and decision-making for preparedness and anticipatory actions. Given the nature of agricultural subsectors and their regional and subregional variability, understanding the current situation and projecting long-term change can only be achieved through the use of interoperable data and the application of innovative digital solutions.

Information systems and data sharing platforms

Effective, consistent and timely risk communication depends on data sharing to enhance knowledge for planning, policymaking and decision-making. Increasing data availability and creating tools that assist users in linking hazard, exposure, vulnerability, and coping capacity are key to improving both disaster risk knowledge and access to stakeholders.

Prominent data/information sharing platforms include FAO's GIEWS. It provides regular and up-to-date data on factors impacting global food supply and demand conditions, in turn aiding national and regional monitoring systems. This information includes near-real-time earth observation data on drought conditions through the Agricultural Stress Index (ASI) and weekly and monthly food price data across more than 120 countries uploaded onto the Food Price Monitoring and Analysis (FPMA) Tool. This data is also synthesized in outlook reports, aimed at triggering anticipatory actions and providing evidence for policy decisions. Likewise, the Kenya Agriculture Data Sharing Platform shares and integrates data on early warning, weather, soil, pest and diseases. The Vulnerability Analysis and Mapping Data Visualization (VAM DataViz) platform [111] of the World Food Programme (WFP) provides similar data to the HungerMap Live.[112]

Global organizations such as the UNDRR work with stakeholders to provide more actionable risk information to inform decision-making through standardized risk data.[113] The DELTA Resilience system standardizes data collection and analysis on disaster impact across sectors and replaces the Desinventar database. It ensures consistency and comparability across regions by improving data integration and analysis and expanding the dimensions of monitored impacts to capture non-economic dimensions such as cultural losses, health and well-being food security, biodiversity and ecosystem health.[114] DELTA Resilience also tracks the impacts of climate-induced slow-onset events and processes that have uncertain onset or end dates but cause significant losses and damages.[115]

By incorporating data standards, definitions and taxonomies to create a harmonized database of disaster impact, the DELTA Resilience demonstrates the power of data interpolation and supports cross-border data comparability. By understanding how hazards interact with vulnerable communities, the database aims to advance disaster risk knowledge for different social groups, places and sectors. Converting data and information into insights for better multilevel decisions and action helps strengthen DRR. Better disaggregated data from cross-cutting sectors, such as agriculture, would improve impact analysis by comparing baseline conditions with observed effects and informing more sophisticated analysis.

Remote sensing and advanced risk assessment

Remote sensing can be very useful for disaster risk management (DRM), as it allows for quick data collection before and after disasters. Remote sensing includes satellite imagery, aerial images, and data from ground-based sensors like radar and laser scanning. Additionally, satellite-based observations provide real-time data for EWS, crop production models and disaster impact assessments. Instruments like MODIS, ASTER, Landsat, and Sentinel can be used to compile hazard maps and assess disaster impacts. The use of unmanned aerial vehicles (UAVs) and ground-based sensors is less common but offers high-resolution data for detailed assessments. GIS is essential for generating maps, analysing risk indicators, and visualizing data, often integrating remote sensing and Global Positioning System (GPS) data.

Advances in technology, including AI, ML, IoT and crowdsourcing, have enhanced geospatial approaches to DRM, enabling more precise and timely assessments, with smartphone applications providing real-time information and facilitating community reporting. Cloud computing and AI and ML tools employ cutting-edge DRM technologies. Cloud computing enables faster and more efficient processing and analysis of vast datasets and is arguably one of the most significant advances for disaster risk knowledge. However, the required computing power, by conventional means of desktop computing, may often be difficult to access for many stakeholders.

AI and ML have further enhanced the ability to forecast hazards and improve DRM. For example, Google's GraphCast uses AI models to provide faster, more accurate global weather forecasts.[116] Similarly, NVIDIA's Fourier Forecasting Neural Network offers an advanced global weather prediction model, delivering weeklong forecasts in less than two seconds, far quicker than existing methods like the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS), while maintaining or improving accuracy.[117] Additionally, data platforms such as digital land cadastres provide accurate geospatial data on land ownership, use and characteristics. This data supports risk assessment, planning, and response efforts by identifying vulnerable areas and informing land use decisions. By integrating cadastral data with hazard maps and emerging technologies like AI and ML, these platforms can assist in zoning regulations, the development of disaster-resilient infrastructure and evidence-based policymaking.

Climate risk assessment tools

There are several challenges in translating disaster risk data into knowledge and actionable information, including limited specialist skills, the time needed for location-specific analysis and the difficulty in communicating with diverse stakeholders using a common language. To overcome these challenges, new information platforms using cloud computing and GIS have been developed. For example, OpenForis is a suite of tools, including EarthMaps and Earth Engine, developed as a collaboration between FAO and Google.[118] These tools successfully support situational analysis and make results accessible, hence providing a more concerted approach for DRR.

FAO's Hand-in-Hand (HiH) initiative provides integrated analyses via advanced geospatial modelling and analytics to identify key areas for raising incomes, improving nutrition and building resilience, such as developing value chains, improving water management, and introducing digital services and precision agriculture.[119] HiH offers an increased speed of data sharing and analytical tools, including analytical layers for elevating risk knowledge and setup cost reduction. One example of these tools is the CRTB, which grants access to high-quality climate data to be layered onto socioeconomic, food security and agricultural data.[120]

The CRTB is an open-access resource hosted on FAO's Agro-informatics Geospatial Platform that harnesses data from FAO and other leading public data providers across the United Nations, NGOs, academia, the private sector and space agencies. This dataset equips stakeholders and policymakers with up-to-date information to enhance climate resilience in agricultural projects, policies and decision-making. It also includes capacity development efforts (e.g. training workshops and technical support) for users to effectively interpret data and apply the tool in a real context. The CRTB has benefited from financial and technological support provided by FAO at zero cost, and contributes to the implementation of FAO's Strategy on Climate Change by informing evidence-based interventions and decision-making using updated climate science and data in over 200 projects.[121]

The CRTB aims at addressing risks effectively by visualizing high-risk areas and identifying key weaknesses in climate risk management across the project cycle. It integrates observed and projected climate hazards with their impacts on agricultural systems and communities, providing tailored recommendations for agricultural transformation and adaptive capacities of farmers and rural communities through climate-resilient practices and technologies.[122]

The CRTB is designed for early-stage climate risk screening, making it valuable to project design teams and policymakers. However, users can also access geospatial data for each climate risk component and tailor their risk analysis by overlaying climatic, geographic, social and economic factors. The tool can be further customized for local, regional and national purposes, integrating local high-resolution and specific datasets. The platform's flexibility enables integration with other FAO tools.

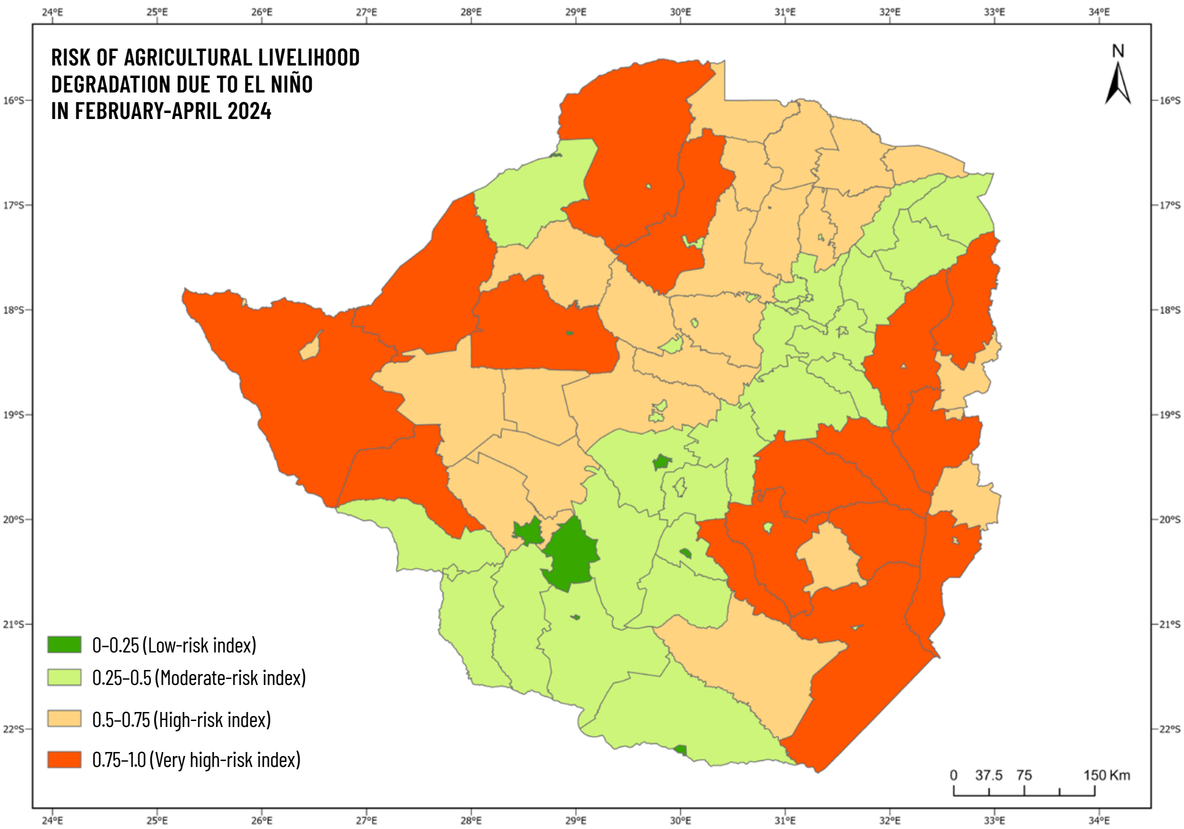
The CRTB combines a large number of high-resolution geospatial data from climate, socioeconomic and environmental datasets, provided by, for example, the World Bank, the UNDP, the Intergovernmental Panel on Climate Change (IPCC) Atlas, FAO's Global Information System on Water and Agriculture (AQUASTAT) and FAOSTAT, the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), the National Aeronautics and Space Administration/Consultative Group on International Agricultural Research (NASA/CGIAR), the Heidelberg Institute for International Conflict Research (HIIK), the Internal Displacement Monitoring Centre (IDMC), and the Global Data Lab, into a single, user-friendly platform. By doing so, the CRTB ensures a more holistic and accessible analysis of climate risks and reduces the technical barriers for users with limited GIS expertise, while also enhancing the capacity of project developers, policymakers and climate funds to design tailored interventions. The CRTB integrates these data with a comprehensive framework based on the IPCC's latest climate risk definition and enables faster, more accurate and cost-efficient climate resilience programming.[123]

Risk mapping and early impact assessment

The ability to understand geographical differences in exposure is another key element for DRR. Risk mapping is highly beneficial at a regional or national level, especially in anticipating and preparing for specific hazards. Risk maps create an objective, data-driven perspective that can provide forecasts and warnings for context- or sector-specific challenges to be translated into intervention strategies.[124] Multihazard risk mapping is an ongoing area of research, and inevitably seeks opportunities for harnessing ML.[125] The Data in Emergencies (DIEM) initiative, ahead of the 2023 El Niño and 2024–2025 La Niña is a recent example of risk mapping in the Southern African Development Community (SADC) region.

El Niño is associated with heightened risk to agriculture and significant impacts. Assessing

FIGURE 21
EL NIÑO RISK INDEX, ZIMBABWE



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.
Source: Authors' own elaboration based on DIEM app and FAO. n.d. *DIEM event viewer*.
[Accessed on 1 August 2025]. https://data-in-emergencies.fao.org/pages/diem_eve. Licence: CC-BY-4.0.

the impacts of this transnational meteorological hazard requires considerable layers of data at different stages of the hazard, as well as historical records that feed into time-sensitive decision-making. FAO's DIEM and GIEWS have been able to support and collaborate with SADC member states in leveraging new digital solutions to address the challenges of reliable, timely, accurate, and granular information ahead of and during the 2023/24 El Niño agricultural season.

The process required three stages. First, a clear understanding of El Niño-related risk components with negative agricultural livelihood outcomes: hazard (historical probability of having El Niño-led rainfall anomalies), exposure (maize main seasonality aspects from start of season to end of season), and vulnerability (underlying conditions that could exacerbate the impact of rainfall anomalies on crop failure and livelihoods). By doing this, risk "hotspots" were highlighted, permitting prepositioning of resources for further impact assessment at the end of the agricultural season. Second, data on food security, livelihoods and agricultural monitoring were gathered during the cultivation and planting period to provide timely updates on the effects of the disaster. Areas at the highest risk were oversampled to increase the precision of the data. Data was collected with computer-assisted telephone interviews (CATI), a technology that can improve data collection in certain contexts. Third, the measure of hazard impact must be conducted on time and at a sufficient granularity to determine the scale of the required support and the most efficient use of response resources. During this process, a layering of data from multiple sources (household surveys, damage and loss assessments, remote sensing, key informant interviews for seed security), leveraging different levels of digital technology, results in multidimensional views of the impact of El Niño.

DIGITAL ADVISORY AND EXTENSION SERVICES

Digital innovations can improve how agricultural knowledge and advisory services reach farmers, transforming conventional extension systems into dynamic, responsive and personalized support networks. Such digital advisory services bridge critical information gaps and provide farmers with timely, context-specific guidance that enhances their decision-making capabilities and resilience to various risks.

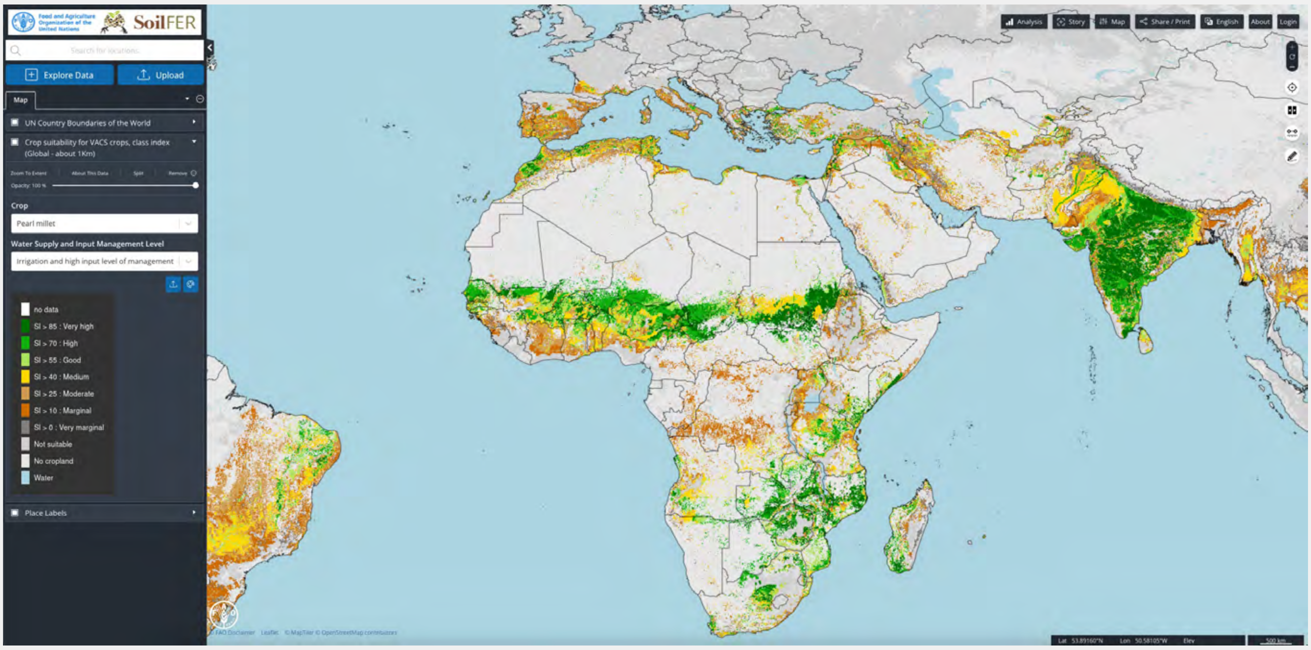
Soil health advisory systems

Digital technologies have significantly changed soil health assessment exercises and related information. Healthy soils form the foundation of agricultural growth, healthy and nutritious food production, and essential ecosystem services.[126] Improving soil health is key to combatting climate change through carbon sequestration and customization.[127] Roughly 95 percent of the food supply relies on healthy soil – maintaining soil structure, improving water retention and increasing carbon sequestration. Farmers lack easy access to soil health assessments and the identification of nutrient balance. This leads to the progressive decline of soil quality, affecting productivity and the environment.

Digital technologies move away from simple soil sampling and laboratory testing and allow for large-scale soil mapping with the support of remote sensing and ML. Soil reflectance spectroscopy, both in laboratories and via satellite and unmanned aerial systems (UASs), allows visualizing soil characteristics (e.g. mineralogy, organic matter, texture and colour) within the visible near infrared (vis-NIR) spectrum (400 to 2 500 nm). Mid-infrared (MIR) spectra have also proven highly effective in predicting various physical, chemical and biological attributes of soil.[128] This vast amount of generated data represents a significant opportunity for farmers to benefit from soil health advisory services but also poses a challenge of how these data can be translated into actionable information.

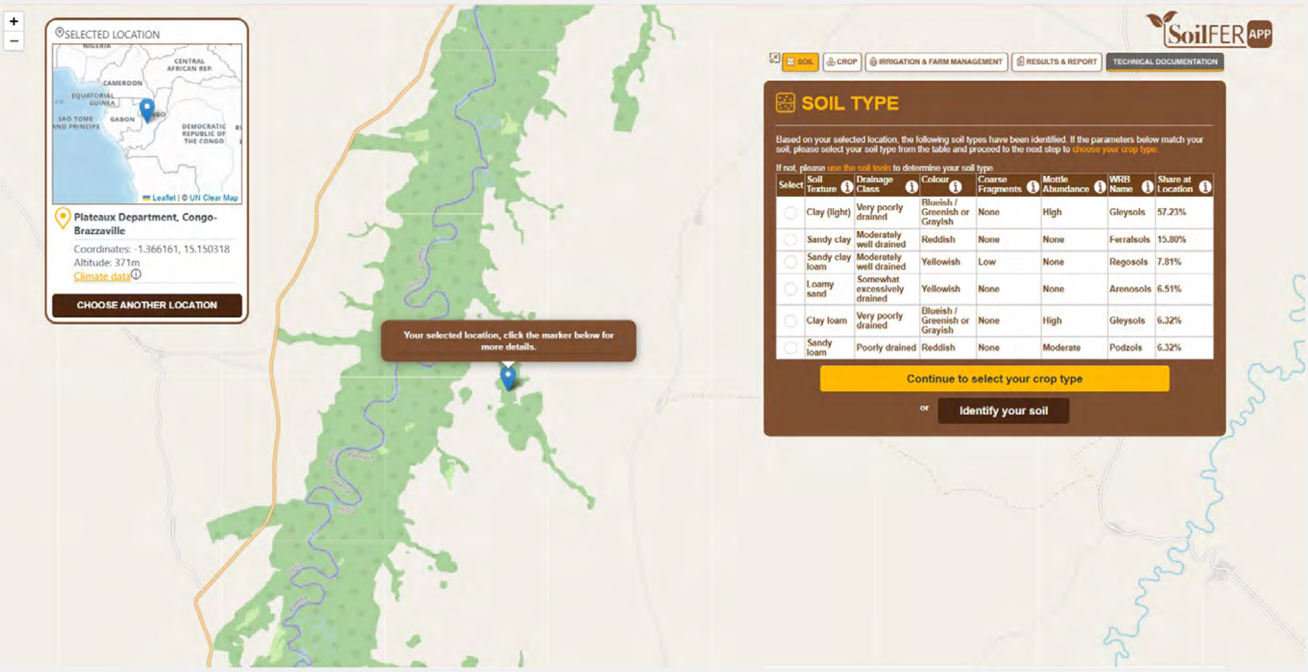
The SoilFER project aims to match soil health data with fertilizer recommendations.[129] SoilFER uses extensive geospatial data and information on soil management, crop selection, and input practices to promote the efficient use of fertilizers, sustainable farming practices, and the selection of major and opportunity crops to positively impact soil health and the livelihoods and resilience of farmers. The SoilFER global geospatial platform (see FIGURE 22) was launched at the Sixteenth meeting of the Conference of Parties to the Convention on Biological Diversity (COP 16) in Riyadh in December 2024, »

FIGURE 22
SoilFER GEOSPATIAL PLATFORM



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Republic of the Sudan and the Republic of South Sudan has not yet been determined. Final status of the Abyei area is not yet determined.
Source: Author's own elaboration based on FAO. 2025. SoilFER geospatial platform. In: *FAO*. [Cited 1 August 2025]. https://data.apps.fao.org/soilfer/?lang=en

FIGURE 23
SoilFER APP FOR CROP SUITABILITY – SOIL TYPE SELECTION



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.
Source: Author's own elaboration based on FAO. 2025. SoilFER geospatial platform.
https://data.apps.fao.org/soilfer/?lang=en

» and can be employed to assess the potential for growing different crops for a specific land area, the interaction between soil types, irrigation practices, climate and soil characteristics, while evaluating scenarios (also across countries) of different levels of input management. Similarly, practitioners and extension services can assess and compare the gap between obtained yield and attainable yield with other areas, crops and management options (FIGURE 23).

Other solutions also offer similar innovative approaches. Digital soil health kits help communities check their soil health and access tailored agronomic advisories based on their type of soil and crops.[130] For large-scale farming, solutions such as SoilOptix help optimizing inputs and maximizing yields by collecting and analysing field data.[131] Innovative Solutions for Decision Agriculture (iSDA) built the first field-level soil map for Africa, with more than 20 soil properties at a resolution of 30 metres.[132] This open-source platform supports advisory and analytical functions and enables informed decision-making through the AI-based "virtual agronomist", which communicates and delivers tailored, data-driven advice via a call-centre modality. [133]

Water management advisory services

Worldwide, agriculture accounts for 70 percent of freshwater withdrawals, with growing pressure on water supplies. Hence, sustainable water resources management remains critical in agriculture.[134] Drought and floods lead to crop failure, soil degradation and food insecurity. Digital technologies and innovations, such as real-time satellite data, help countries and communities monitor and sustainably manage their use of groundwater, such as the Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention (MARVI) project in India.[135] Global efforts such as Geo Aqua Watch improve the coordination, delivery and utilization of water quality information using satellites.[136] In Kenya, the Water Management as a Service Platform (WMaaSP) decision-making tool uses sensors to provide supply and demand patterns based on groundwater extraction data.[137]

FAO's WaPOR project provides this data and is ultimately improving water management.[138] For example, irrigation scheduling apps on smartphones, like the Irrigation Reference to Enhance Yield (IREY) app in Tunisia, translate and combine satellite data with local insights to provide actionable information to farmers (FIGURE 25). IREY uses a wide variety of inputs, including earth observation data from WaPOR and data provided by the farmers through the app for tailored information on the development of wheat crops. It optimizes irrigation practices towards more sustainable water use and improved crop yields

Agrometeorological advisory services

Agrometeorological (agromet) advisory services help farmers make informed decisions on water and fertilizer management, pest and disease control, sowing and harvesting schedules, and weather forecasting. Agromet advisories are driven by data availability and quality, as well as by the capacity to analyse data. They have positive impacts on agriculture only when the context- and location-specific information reaches the users (e.g. farmers) with the support of mobile technologies, in a timely manner and in the right language.[139] Agromet advisories combining weather forecasting and climate and crop modelling enable communities to enhance their climate-informed decision-making. By focusing on context-specific needs and comprehensible risk information, agromet advisories can adopt a people-centred approach for climate services through the incorporation of feedback mechanisms between scientists, governments, private institutions and farmers.[140]

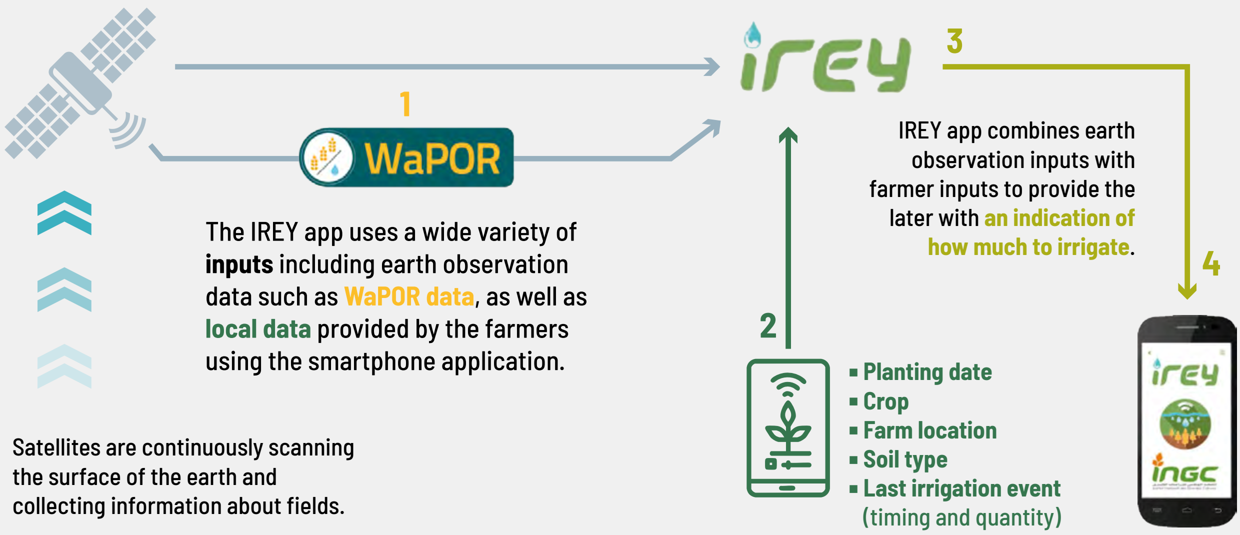
In India and West Africa, agromet advisories provide economic benefits to farmers. In Haryana, India, farmers reduced input costs by approximately USD 29.65 per hectare for wheat and USD 44.48 per hectare for paddy rice.[141] In Raichur and Bidar districts, the yields of pigeon pea, soybean and pearl millet increased by 233, 98 and 318 kg/ha, respectively, when agromet advisories were utilized.[142] In the entire study area, the value addition for these three crops in a single season is of USD 9.66 million. Similarly, in Karnataka and Andhra Pradesh, agromet advisories increased farmers' profit from 12 to 33 percent.[143]

In Niger and Mali, agromet advisories improved farmers' incomes by USD 40 per hectare at the »

FIGURE 24
SoilFER APP FOR CROP SUITABILITY – RESULTS AND REPORT

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.
Source: Author's own elaboration based on FAO. 2025. SoilFER geospatial platform.
In: *FAO*. [Cited 1 August 2025]. https://data.apps.fao.org/soilfer/?lang=en

FIGURE 25
INFORMATION FLOWS FROM THE FIELDS TO FARMER SMARTPHONES



The **Bouheurtma irrigation scheme** is the pilot area in Tunisia for IREY. It spans 13 000 hectares in the Jendouba governorate; there IREY has demonstrated measurable improvements: **reduced water usage** and **enhanced productivity**.

Source: Authors' own elaboration.

» start of the season, USD 24 per hectare during the cropping season and USD 10 per hectare by the end of the season.[144] In Southwestern Niger, agromet advisories increased farmers' incomes by USD 116 on average for a 3-hectare farmland.[145] In Burkina Faso, agromet advisories reduced production costs by 40 percent and increased income by 41 percent.[146] Agromet advisories can also have environmental impacts, like in the Burkina Faso study, where agromet advisories reduced fertilizer use by 50 percent.

Many other existing platforms cater to large-scale producers, supported by corporate entities that embrace full digital integration.[147] However, these sophisticated tools often come with costs that farmers cannot sustain. Emerging transformative solutions, such as AI-driven chatbots and decision-support tools, can provide real-time and context-specific advice across the value chain, empowering farmers and vulnerable groups with actionable insights.

Integrated digital advisory platforms

FAO's SEED Hub in Sri Lanka provides an example of a transformative digital intervention.[148] Developed by the Agrifood

TABLE 2

SUMMARY OF IMPACTS OF AGROMET ADVISORY SERVICES*

LOCATION	CROP	INPUT COST REDUCTION		OUTPUTS	RETURNS		STUDY
		INPUTS	PRODUCTION COSTS	YIELD INCREASE	INCREASED INCOME	INCREASED PROFIT	
Haryana, India	Wheat	USD 29.65 per hectare					(Manjunath *et al.*, 2024)[i]
	Paddy rice	USD 44.48 per hectare					
Raichur and Bidar districts, India	Pigeon pea			233 kg/ha			
	Soybean			98 kg/ha			
	Pearl millet			318 kg/ha			
Karnataka and Andhra Pradesh, India	Various					12% to 33%	(Dupdal *et al.*, 2021)[ii]
Niger and Mali	Various				USD 40 per hectare at the start of the season, USD 24 during the season, USD 10 at the end of the season		(Bizo *et al.*, 2024)[iii]
Southwestern Niger	Various				USD 116 on average for 3 hectares		*(Seydou et al.*, 2023)[iv]
Burkina Faso	Various	50% in fertilizer usage	40%		41%		(Tarchiani *et al.*, 2021)[v]

Note: * For the entire study area, this translates to a value addition of USD 9.66 million for these three crops in a single season.

Source: Authors' own elaboration using referenced literature: [i] Manjunath, K.V., Maiti, S., Garai, S., Reddy, D.A.K., Sahani, S., Panja, A. & Jha, S.K. 2024. Impact of climate services on the operational decision and economic outcome of wheat (*Triticum aestivum*) and rice (*Oryza sativa*) cultivation in Haryana. *The Indian Journal of Agricultural Sciences*, 94(3–1): 116–123. https://doi.org/10.56093/ijas.v94i3.148633; [ii] Dupdal, R., Dhakar, R., Rao, C.A.R., Samuel, J., Raju, B.M.K., Kumar, P.V. & Rao, V.U.M. 2021. Farmers' perception and economic impact assessment of agromet advisory services in rainfed regions of Karnataka and Andhra Pradesh. *Journal of Agrometeorology*, 22(3): 258–265. https://doi.org/10.54386/jam.v22i3.187; [iii] Bizo, I.M., Traore, B., Sidibé, A. & Soulé, M. 2024. Effectiveness of climate information services: An evaluation of the accuracy and socio-economic benefits for smallholder farmers in Niger and Mali. *Frontiers in Climate*, 6: 1345888. https://doi.org/10.3389/fclim.2024.1345888; [iv] Seydou, T.H., Agali, A., Aissatou, S., Seydou, T.B., Issaka, L. & Ibrahim, B.M. 2023. Evaluation of the impact of seasonal agroclimatic information used for early warning and farmer communities' vulnerability reduction in southwestern Niger. *Climate*, 11(2): 31. https://doi.org/10.3390/cli11020031; and [v] Tarchiani, V., Coulibaly, H., Baki, G., Sia, C., Burrone, S., Nikiema, P.M., Migraine, J.-B. & Camacho, J. 2021. Access, uptake, use and impacts of agrometeorological services in Sahelian rural areas: The case of Burkina Faso. *Agronomy*, 11(12): 2431. https://doi.org/10.3390/agronomy11122431

Economics and Policy Division (ESA), the Digital FAO and Agro-Informatics Division (CSI) in collaboration with the Ministry of Agriculture, the Department of Meteorology, and the Hector Kobbekaduwa Agrarian Research and Training Institute of Sri Lanka, the SEED Hub app delivers free-of-charge, geo-localized, timely and integrated advisory services. The app empowers farmers with critical information such as weather forecasts, crop management practices, market prices, agrometeorological and agromarket advice. During the 2023/2024 Maha season pilot, farmers using the SEED Hub app experienced significant gains compared to their peers without access to the app. On average, they achieved a 26 per cent increase in rice productivity, a 48 per cent boost in rice sales, and received 33 per cent higher market prices. Additionally, they diversified their production with an average of 0.73 more crops per farmer. Successes were also observed at the village level, as most farmers were accessing and sharing information even when only a few farmers were directly receiving information on the app. This collective knowledge sharing is an important reference for other digital advisory services in contexts with low digital literacy.

Strengthening farmers' collective resilience offers a powerful opportunity for impactful, integrated, and holistic interventions. While notable progress has been made in agricultural and marketing decision-making, the lack of observed improvements in household food security underscores the complex link between agrifood systems and household consumption – highlighting critical areas where further coordinated support is needed. Farmers also need access to financial markets – including affordable credits and insurance – to manage risks and invest in productivity enhancing inputs. Furthermore, systemic infrastructure gaps – such as inadequate post-harvest storage, poor road networks and limited access to markets – can hinder their ability to fully benefit from improved access to information. To fully unleash the potential of digital decision tools like the SEED Hub, they need to be mainstreamed into existing agricultural systems as part of a more comprehensive approach, integrating digital extension services with complementary agricultural interventions and DRR plans and strategies.

Other successful examples include a community video-based extension by Digital Green to encourage farmers to improve agronomic and livestock practices[149] and "Uliza", an extension that combines radio, mobile phones and interactive voice response to enable listeners to communicate and exchange information in local languages with their radio station quickly, easily and free of charge.[150] These have proven to be effective in leveraging community volunteers and incorporating digital solutions. Kuza is another example that provides bundled solutions, such as agricultural advisories, access to quality input and credits to transform rural youth into agripreneurs.[151] A comprehensive list of examples can be found in FAO's AgriTech Observatory[152] and the Digital AgriHub Dashboard.[153]

While these initiatives have achieved notable success, their impact can be further amplified by addressing key opportunities – such as enhancing digital literacy among farmers, strengthening human capital, and the increasing investment in rural infrastructure.[154,155] Despite these advances, challenges such as regulatory barriers, costs and integration into existing DRR frameworks remain, highlighting the need for continued collaboration and strategic investment. ■

3.2 FROM EARLY WARNING TO RESILIENT ACTION

The digital tools and technologies examined in the previous section provide the foundation for transformed risk management, yet their true value emerges only when they translate into timely, effective action that protects lives and livelihoods. This section examines how digital innovations enable the critical shift from reactive response to proactive prevention—demonstrating how early-warning systems inform anticipatory actions, how predictive analytics guide decision-making before disasters strike, and how integrated digital platforms support the building of long-term resilience. By exploring the operational deployment of these technologies across disease surveillance, pest monitoring, food security assessment, and risk transfer mechanisms, we reveal the practical pathways through which digital transformation delivers measurable benefits to farmers and communities facing mounting disaster risks.

Digital technologies support early-warning systems in offering insights that enable policymakers and communities to take anticipatory actions. EWS can save lives and assets that are worth at least ten times their costs.[156] For every USD 1 invested in anticipatory actions, FAO estimates that rural families can gain up to USD 7 in benefits, including avoided agricultural losses.[83] There has been a shift towards recognizing the importance of multihazard early-warning systems (MHEWS) in managing risks and their impacts across sectors and systems, including agrifood systems. Effective MHEWS are people-centred and inform vulnerable communities of anticipated risks and crises towards taking appropriate DRR actions. The United Nations Early Warnings for All initiative brings together the broader United Nations system, governments, civil society and development partners across the public and private sectors to enhance collaboration to address gaps and deliver people-centred, end-to-end MHEWS.[157] Initiatives to better forecast hazards and their impacts and deliver critical information, ultimately translate into more effective policies and actions for increasing the resilience of farmers and agrifood systems.

EARLY-WARNING SYSTEMS AND SURVEILLANCE

The spread of transboundary pests and diseases is of growing concern. Climate anomalies increase the risk of transmission due to expanding breeding environments of vectors, or prolonged and unseasonal periods of transmission. Digital technologies can integrate multiple layers of information into disease and pest monitoring systems to provide a better understanding of these biological hazards and elevate the predictive power and functionality of EWS. This permits planners to anticipate outbreaks more effectively and reduce the likelihood of widespread destruction.

Disease surveillance and monitoring systems

To be an effective part of the decision-making system, the data gathered often requires authoritative analysis and processing. FAO and the World Health Organization (WHO) underline the importance of promoting digital solutions for accelerating disease identification, reporting, warning and diagnosis. For example, the direct and indirect impact of FMD on agriculture has been estimated to be between USD 6.5 and USD 21 billion.[158] The World Organisation for Animal Health (WOAH) and FAO support the control and monitoring of FMD to reduce related impacts. The complexity of tracking and controlling a transboundary disease such as the FMD virus requires a significant amount of epidemiological data.

Conveying up-to-date information about critical events in near real time is crucial for effective disease control and prevention. New technologies have revolutionized pathogen surveillance, with advanced computational tools and AI enabling real-time data collection from diverse sources, facilitating rapid outbreak identification and tracking. The FAO World Reference Laboratory for FMD and EuFMD developed the OpenFMD platform to facilitate global FMD surveillance and share data via analytical tools such as FMDbase,[159] FMDtype,[160] FMDwatch,[161] PRAGMATIST[162] and FMDnext. These tools leverage genetic and epidemiological data to enhance understanding of FMD evolution and spread. OpenFMD addresses data gaps, improves transparency and supports evidence-based decision-making. These exemplify how integrating digital technologies and open data in pathogen surveillance enhances our ability to detect outbreaks early and respond swiftly, which ultimately reduces impacts.

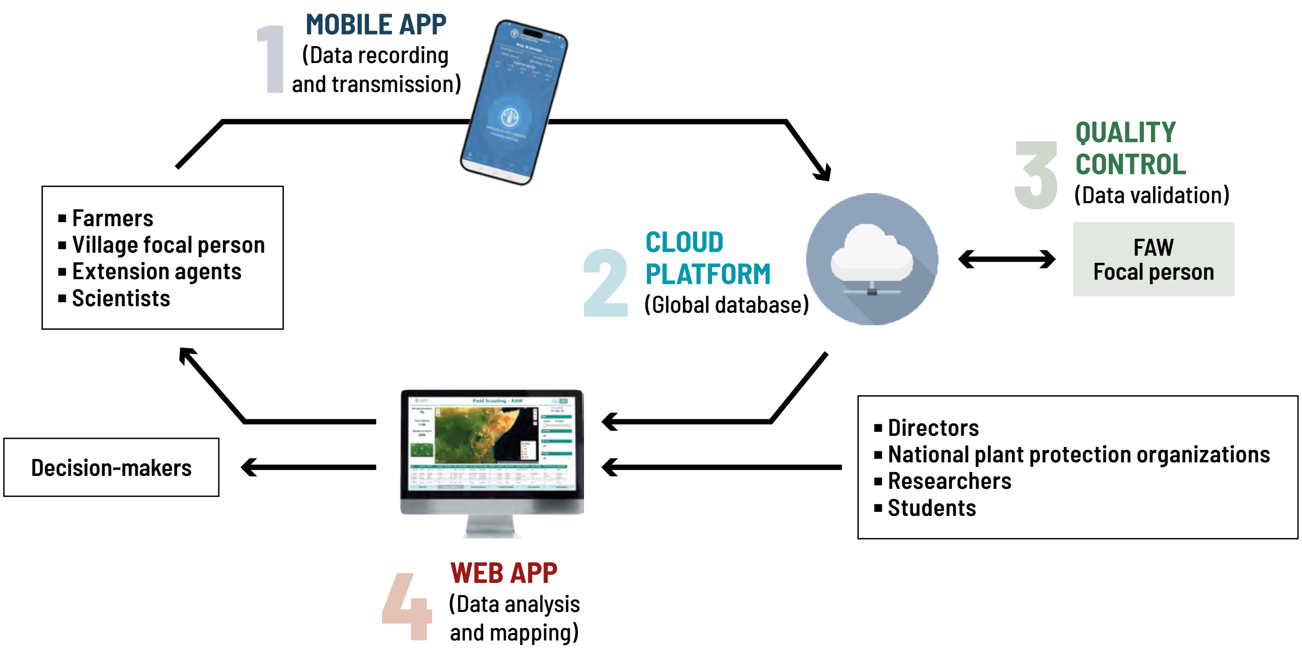
Low-cost, accessible, centrally-maintained digital solutions enhance pest identification, control, surveillance and data collection. FAO supports disease monitoring with real-time information systems such as EMA-i+, EIOS and GLEWS+. The Event Mobile Application (EMA-i) is free and available to countries seeking to adopt digital reporting systems for animal disease. EMA-i helps bridge the digital gap by supporting more than 4 000 users in 15 low-income countries who have reported over 60 000 disease suspicions to the veterinary services in the last three years. By using EMA-i, authorities become aware of these events as soon as they are notified, with digital systems connecting all levels of governmental preparedness and response in real-time.

FAO has also made available the EMPRES Global Animal Disease Information System (EMPRES-i+). An early warning team monitors weekly information collected through the over 130 FAO country offices, complemented with media scanning with the EIOS tool, developed by WHO. FAO uses EIOS to scan media for potential signals of animal diseases and makes the collected information publicly available in EMPRES-i+. Animal health threat updates are also discussed weekly within FAO's network to improve awareness and preparedness around the globe.

When the global system detects disease alerts with possible zoonotic potential, the information is shared with WHO and WOAH. The Joint FAO–OIE–WHO GLEWS+ stands as a critical defence for global health. Between 2018 and 2023, 243 events covering 20 zoonotic diseases were reported using the platform, allowing information to be shared among the three partner organizations. In 2021, GLEWS+ conducted a joint risk assessment for SARS-CoV-2 transmission in fur farms. This assessment helped countries better manage disease risk and improve surveillance.

In Cambodia, efforts are ongoing to use disease surveillance innovations, providing lessons to address region-specific challenges. The concept of "smart markets" leverages cutting-edge technologies to enhance surveillance in traditional food markets – hotspots for zoonotic spillovers – by providing timely, actionable data for stakeholders. FAO deployed air samplers in conjunction with metagenomic analysis to capture high-resolution data on pathogen presence and diversity in traditional food markets. These surveillance data are comparable to, and in some cases even more comprehensive than, traditional methods involving the sampling of chickens and ducks. This highlights the efficiency and robustness of this technology in detecting endemic and emerging pathogens in complex environments. However, further evidence is necessary to support investments, effective communication strategies and addressing disparities in digital readiness.

FIGURE 26
THE FAMEWS WORKING CONCEPT/DATA FLOW MECHANISM



Source: Authors' own elaboration.

Pest monitoring and early-warning systems

The fall armyworm (*Spodoptera frugiperda*) is a highly mobile transboundary pest that originates in the Neotropics and can cause a significant loss in a wide range of food, feed and fibre crops. Following its initial detection in West and Central Africa in 2016, FAW spread swiftly across Africa, the Near East, and Asia and the Pacific, affecting crops, imperilling food and livelihood security, and driving pesticide abuse. At that time, there was limited knowledge about FAW's behaviour outside its native range. Therefore, to provide timely and accurate data on FAW and its ecology and spread in new habitats, FAO developed the FAMEWS,[163] with information and communication technology (ICT) support from PlantVillage at Penn State University (FIGURE 26).[164]

This integrated system uses field scouting and pheromone traps to monitor FAW. It includes a mobile app for data collection, a cloud-based database, and a global platform for mapping and analysing the information, making it accessible to users. Field-collected data are instrumental in monitoring FAW infestation levels and dynamics across the FAW invasive range, establishing risk zones and steering risk management interventions. Beyond monitoring FAW spread, FAMEWS also connects stakeholders, offering farmers free advice, open-access resources and AI-based FAW identification. FAMEWS is also linked to the global PlantVillage network, giving users access to information on other pests and diseases.

FAMEWS provides tailored decision support through actionable insights supported by pest management protocols and guidance. It establishes a coordinated response to contain the spread of FAW. First, FAMEWS offers a mobile app and a global platform for real-time data collection and analysis, enabling farmers, community focal points and extension agents to report FAW infestations promptly. This facilitates the rapid dissemination of information and allows for timely interventions to reduce crop damage. Second, the data are validated by local staff and analysed to generate detailed maps and reports, supporting decision-making at the farmer, community and national levels. Third, FAMEWS offers training materials, expert guidance and a digital library to promote the adoption of IPM practices, which control FAW populations while reducing reliance on highly hazardous pesticides, thereby supporting biodiversity, environmental sustainability and human health. Fourth, the app includes chat functions and expert resources, fostering collaboration in FAW management and strengthening local resilience. Fifth, it is user-friendly and accessible, with offline functionality and availability in 29 languages, ensuring reach to farmers in remote areas. FAMEWS data are open-access, providing valuable insights to a wide range of users and promoting the exchange of best practices.

Since its launch, FAMEWS has processed data from over 50 000 field scouting events and over 16 000 pheromone traps in more than 60 countries, forming the foundation for advanced forecasting models, EWS and decision support tools at the farm level.[165] FAMEWS has been crucial in improving EWS, preparedness, and decision-making capacities and processes in 18 African countries. Five countries (Burkina Faso, Cameroon, Ghana, Kenya and Mozambique) have reported reduced infestations and associated yield losses. The FAO Global Action for FAW Control continues to promote the FAMEWS for pest monitoring, risk assessments and the implementation of sustainable management practices. Beyond mitigating the pest-related impacts, this approach also bolsters the long-term resilience and sustainability of agricultural systems.

Vector-borne disease early-warning systems

The Rift Valley Fever Early Warning Decision Support Tool (RVF-DST) is another example of an EWS that promotes innovative use of data layers, digital technologies and advanced analytics. Rift Valley fever is an acute, climate-sensitive, vector-borne viral zoonotic disease that significantly impacts livelihoods, markets and human health.[166] Currently confined to Africa and parts of the Near East, it has the potential to spread globally, primarily by mosquito bites (particularly *Aedes* and *Culex* species, and secondarily *Anopheles* species). RVF affects humans and animals like sheep, goats, cattle, buffalo and camels. Early detection and anticipating outbreaks are critical given that the disease causes high mortality in young animals and leads to high abortion rates.[167,168] RVF poses challenges for surveillance because, in endemic regions, it circulates subclinically among animals and mosquitoes. Infected mosquito eggs can survive for years during dry periods, making eradication unfeasible with current methods.

As mosquito populations increase after flood events, RVF is amplified in livestock herds, leading to outbreaks during these periods. Consequently, RVF outbreaks are strongly associated with climate anomalies that lead to these events (including phenomena like El Niño) and further compounded by climate change.[169] Due to the severity and impact of RVF on livestock herds, and the consequential economic impact on agriculture and livelihoods, EWS are essential for helping national authorities implement proactive measures to enhance detection, prevention, and response efforts, and are initiated following RVF alerts. This includes enhanced risk-based surveillance, deployment of sentinel herds, well-equipped laboratories for accurate diagnostics, targeted vaccination campaigns and improved readiness through updated contingency plans.[170]

FAO monitors and forecasts RVF in African countries with the web-based RVF-DST. This integrates real-time risk maps, historical data, and expert knowledge and provides monthly and eight-day risk updates for the African continent.[171] Risk mapping modelling has progressed from snapshots of RVF's ecoepidemiology across different ecosystems to a dynamic model that tracks the evolution of RVF risk over time and identifies climate variations that influence vector dynamics.[172,173,174]

The RVF-DST integrates multiple data sources for continuous monitoring of RVF risk, including climate; livestock and wild herbivore populations susceptible to the virus; past and current RVF occurrences; human populations; marketplaces; road networks; animal trade routes; water bodies and irrigation areas; land cover; and soil characteristics. The RVF-DST is also integrated into the Agro-Informatics geospatial platform to enhance the interoperability of FAO's geospatial data and ensure cost-effective maintenance and sustainability of FAO applications.

The RVF-DST provides a risk map, using proxy measures, to highlight areas of potential risk of RVF Vector Amplification. It also allows spatial analysis on polygons or points or subnational administrative boundaries, namely: comparison of monthly precipitation (total and cumulative) with long-term averages; historical distribution of land under normalized difference vegetation index (NDVI) anomalies; quantity of human and livestock population at risk (in areas with identified NDVI anomalies); and multifactor radar charts of features that are relevant in areas presenting NDVI anomalies.

The RVF-DST also supports custom data uploads and trend tracking of RVF risks with comparative charts. Features include printable reports, metadata links, real-time data sharing, and story maps for early warning, with content available in English and French. Future innovations and planned features include the integration of multicriteria decision analysis (MCDA) into the tool to enhance risk categorization linked to informed actions/recommendations, and accessing the RVF-DST via FAO's EMPRES-i+ interface. EMPRES-i+ provides updated animal disease information at the national, regional and global levels, supporting early warning and response to transboundary animal diseases like RVF.

To integrate the RVF-DST into governance pathways, supporting processes are required, including training to optimize its use for real-time data sharing, environmental risk monitoring and disease forecasting. A monthly verification and alert determination process follows, during which a panel of experts at the national, regional and global levels conducts a qualitative risk assessment combining real-time data from the RVF-DST with local sources and expert knowledge to verify results and determine whether conditions warrant an RVF alert. The results, along with a three-month risk prediction, are included in the weekly internal FAO Animal Health Threat Update (AHTU) and shared with stakeholders for informed action; and continuous monitoring with satellite technology and high spatial and temporal resolution data.

The RVF-DST has been successfully applied in major RVF outbreaks in the United Republic of Tanzania (2007), Kenya (2018) and Uganda (2018 and 2024).[161] In the United Republic of Tanzania, heavy rainfall in late 2006 led to increased vector amplification suitability, with a two-month lag before the outbreak in February 2007. In Kenya, heavy rainfall from February to April 2018 caused a spike in vector amplification suitability, followed by the first outbreaks in late May/early June. In Uganda, similar patterns occurred in 2018 and 2024, with joint FAO-IGAD alerts issued 2–3 months before the outbreaks. In the United Republic of Tanzania, risk-based sero-surveillance was conducted in high-risk areas, with results suggesting RVF is endemic in the surveyed areas.

Collaboration with government bodies, regional cooperation and local capacity building have been emphasized as a success factor. For example, following the FAO-IGAD joint alert of May 2024, Rwanda initiated proactive, nationwide risk-based vaccination campaigns to mitigate the risk of an RVF outbreak. By August 2024, the only reported outbreak remained confined to Ngoma district, affecting a limited number of animals over a short period. The restricted nature and duration of the RVF outbreak are credited to the pre-emptive vaccinations aligned with the alert's recommendations using a One Health approach.

These examples highlight how combining digital tools, surveillance, and expert validation strengthen disaster response through collaboration between FAO, national veterinary services and regional partners. To further enhance the RVF-DST's capacity, additional data on agricultural losses from RVF outbreaks are needed, such as livestock mortality, economic impacts on trade and tourism, and costs to agricultural industries.

Since 2018, FAO has issued 19 RVF alerts in Africa, 16 of which were jointly issued with IGAD for Eastern Africa, providing information on risk areas and guidance on mitigation and control measures.[175] FAO has also developed manuals on RVF prevention, control and national contingency planning, along with an action framework. A key part of FAO's work involves building the EWS capacities of countries. To address technical gaps, FAO has been delivering a training programme on the use of the RVF-DST at both the regional and country levels since 2021.

Food security and nutrition early warning

The Integrated Food Security Phase Classification (IPC) was developed in 2004 by FAO's Food Security and Nutrition Analysis Unit (FSNAU) to help flag potential hunger hotspots and provide a common scale for classifying the severity and magnitude of food insecurity and acute malnutrition.[176] The global partnership has evolved to include 20 other organizations involved in improving food security and nutrition analysis.[177] The IPC provides a standardized framework for classifying the severity and magnitude of food insecurity and malnutrition, facilitating better decision-making and resource allocation.[178] Since 1999, the Permanent Interstate Committee for Drought Control in the Sahel (Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel, CILSS) along with the Economic Community of West African States, West African Economic and Monetary Union, United Nations agencies (FAO, WFP, the United Nations Children's Fund), non-governmental organizations (Action Against Hunger, Save the Children and Oxfam), and Famine Early Warning Systems Network (FEWS NET), developed and implemented the Cadre Harmonisé (CH) for the analysis and identification of areas and populations at risk of food and nutrition insecurity in the Sahel and West Africa.

With subsequent lockdowns, the IPC Information Support System (ISS) ensured that the work in assessing and analyzing food insecurity could continue. The ISS ensured that large amounts of data could be shared among experts, which is necessary for an IPC analysis, and enabled more rounds of analysis than in the past, reducing costs associated with centralized gatherings of experts and speeding up the processing of information. This digital solution may have been one of the most impactful advances of the IPC in terms of resilience to changing work environments because of the COVID-19 pandemic. Webinars and e-learning modules also ensured knowledge creation and sharing. Other digital tools, such as CATI, facilitated remote data collection and helped ensure that data for decision-making are up to date, relevant, sufficiently comprehensive and granular. The IPC/CH also developed an API to facilitate integration into other platforms such as Strata,[179] HiH initiative[180] and Food Systems Dashboard.[181]

IPC/CH is built on data-driven consensus between decision-makers for advocacy and action purposes. People and their engagement are therefore central to IPC/CH. The way digital innovations have been integrated into the platform reflects this principle well, even in the context of exploring the role of AI and ML. The use of AI in IPC is being explored to improve efficiency and to increase the coverage and frequency of analyses. Rather than positioning AI as a central tool for classification, the focus is on how it can support experts by automating data processing and summarization, and by flagging geographic areas that may warrant further investigation/updated classifications. This experience with AI in IPC demonstrates how digital tools can streamline established processes, improving efficiency and enabling more timely and targeted analyses. At the same time, it highlights the ongoing need for expert capacity development, consensus building and decision making to ensure AI effectively supports and complements human expertise.

AI systems, however, rely heavily on the availability of high-quality, standardized and granular data to function effectively. Combining human expertise with AI to build a collective intelligence paradigm and ensure context-appropriate interventions can help address data and capacity gaps and significantly support DRR efforts.

ANTICIPATORY ACTION AND RESPONSE

Enhanced risk monitoring platforms

Advanced technical tools, such as geospatial dashboards combined with remote sensing analysis, offer innovative solutions for identifying high-risk areas, supporting smallholder farmers with actionable insights and laying the groundwork for future EWS. For instance, the development of the Agricultural Monitoring Platform (AMP) for the Sudan (see FIGURE 27), a dashboard for monitoring land and water-related risks, can help the country identify vulnerable regions for enhancing DRR and agricultural resilience.[182] The dashboard was developed to analyse risks at a watershed level, a granular spatial scale directly linked to flood risks and agricultural morphological patterns. It integrates a comprehensive array of datasets, including state-wide project coverage, land cover classifications, climate indicators, flood history, security incidents, socioeconomic data and population statistics.

The AMP supports agricultural monitoring and decision-making through a suite of integrated features. It includes net primary productivity (NPP) tracking using WaPOR version 3 data, which monitors carbon productivity across various land cover types over the past five years, allowing for early detection of stress at the watershed and locality levels. FIGURE 28 illustrates monthly deviations in NPP from the five-year baseline across different land cover types.

The platform also incorporates a detailed flood analysis, covering five recent years (2018–2024), based on remote sensing to assess flood extent and duration. In addition, climate analytics provide monthly rainfall trends for the last five years using Climate Hazards Group InfraRed Precipitation with Station data, supporting the evaluation of precipitation variability. The crisis and security tracking component visualizes conflict patterns using armed conflict location and event data (ACLED) data, updated through 2025, enabling users to assess the potential impact of insecurity on agricultural systems. Lastly, the platform includes socioeconomic data, such as population estimates, aggregated at the watershed level, with plans to integrate additional layers, like displacement and returnee data.

Currently in its draft stage, the AMP's features are designed for continuous enhancement. This multilevel approach enables tailored decision-making across administrative, watershed and agroecological zones, enhancing accessibility for national policymakers and localized project stakeholders. The AMP aims to visualize key data as a basis for risk monitoring. The Sudan faces simultaneous challenges of natural hazard-induced disasters, particularly floods and national conflicts. These challenges significantly impact agriculture and food security, especially smallholder farmers who lack timely, localized risk information. The AMP addresses this by mapping flood-prone areas and the locations of crisis events, and monitoring agricultural productivity and historical climate indicators. Its interactive dashboards and region-specific maps allow stakeholders to monitor the impacts of specific »

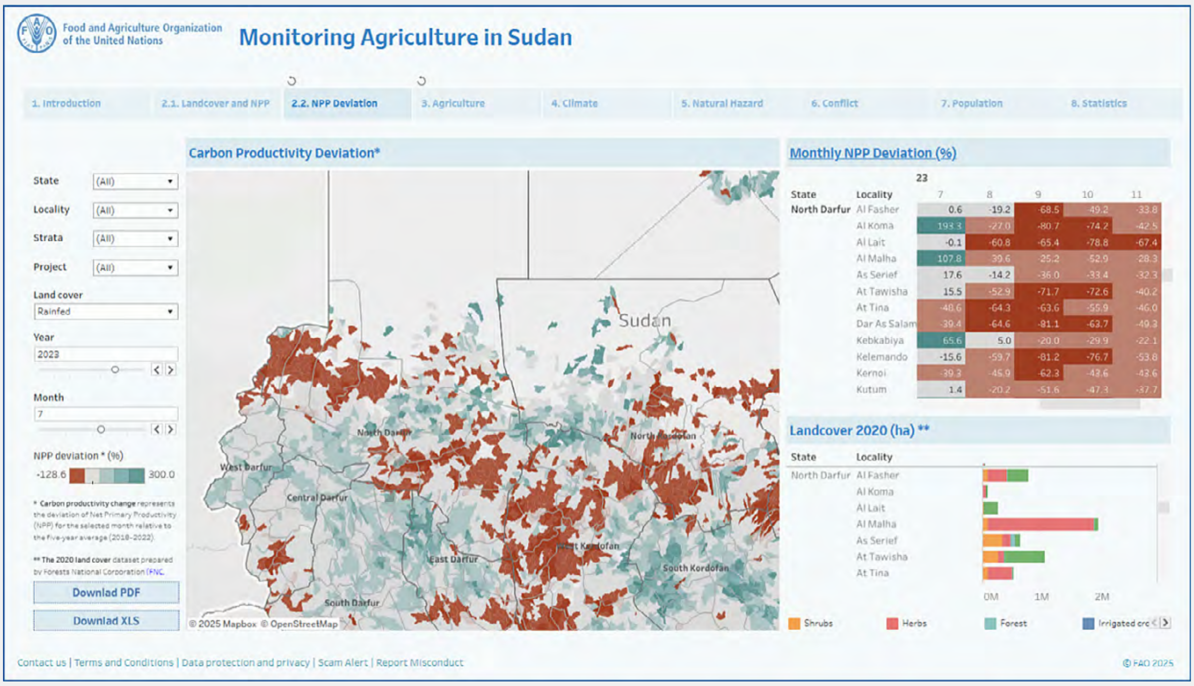
FIGURE 27

OVERVIEW OF THE AGRICULTURAL MONITORING DASHBOARD AND FAO PROJECT COVERAGE

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map. Final boundary between the Republic of the Sudan and the Republic of South Sudan has not yet been determined. Final status of the Abyei area is not yet determined.
Source: Authors' own elaboration based on project coverage from the FAO Representation in the Republic of the Sudan.

FIGURE 28

MONTHLY MONITORING OF CARBON PRODUCTIVITY (NPP) DEVIATION FROM BASELINE ACROSS DIFFERENT LAND COVER TYPES



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.
Sources: FAO. 2019. *WaPOR Database methodology: Level 3 data – Using remote sensing in support of solutions to reduce agricultural water productivity gaps*. Rome. https://openknowledge.fao.org/handle/20.500.14283/ca3750en; and FNC (Forests National Corporation). 2021. *Republic of Sudan National Land Cover Map: 2020 Report*. Khartoum. https://www.fao.org/fileadmin/user_upload/faoweb/Themes__pages/Forests/REDDNFM/Sudan_MRV/Sudan_NFMS_Action_Plan.pdf

» projects and the effects of disasters or conflicts. This facilitates informed decision-making and more effective resource allocation. The AMP supports targeted interventions by identifying high-risk areas and providing real-time, actionable data. This empowers smallholder farmers to make informed decisions on irrigation, planting and resource allocation.

To complement these capabilities, more detailed remote sensing analysis integrates high- and very high-resolution crop monitoring across key agricultural zones. This includes time-series assessments of land use, crop growth and cultivation patterns, with a focus on strategic areas such as the Gezira Irrigation Scheme. Using vegetation indices and satellite-derived productivity metrics, the analysis tracks shifts in major crops like wheat, sorghum and cotton – particularly under the pressure of conflict and environmental challenges.[183] In 2024/25, the cultivated area fell by 57 percent, with wheat declining by 68 percent in area and 72 percent in productivity. [184] These outputs enrich the AMP's capacity to detect risks and guide decision-making, offering an evidence-based foundation for targeting interventions, optimizing resources, and supporting smallholder farmers under crisis conditions.

Predictive analytics for agricultural monitoring

Reliable and timely data on crop yields is essential for short-term cereal supply and demand outlooks, which play a pivotal role in triggering anticipatory actions to mitigate the impact of production shocks, volatile markets and food insecurity. Risk monitoring platforms can facilitate the tracking of global food supplies and production, and the alteration of adverse conditions, thus supporting decision-making.

The Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM) crop monitor is one of these tools.[185] However, access to data from platforms such as GEOGLAM remains a challenge, particularly in regions with limited infrastructure, logistical barriers, conflict and high costs. To address these gaps, digital innovations such as FAO's ML-based prediction method using remote sensing data to predict crop yields are being developed. This represents a step forward in bolstering the reliability, accuracy and interpretability of crop yield forecasts. A key advantage of these models is their spatial applicability, for example, in areas that are difficult to access, such as conflict-affected regions. Through collaboration with universities and research institutions, FAO is pursuing the integration of these methods and data into existing analytical frameworks, addressing critical gaps in standard approaches and enhancing their practical impact.

These models and their outputs have already demonstrated their value in Southern Africa during the 2024 El Niño-induced drought. FAO provided ML-based yield forecasts to country offices and national governments three months prior to the main harvest period. These quantifiable early warnings enabled more effective drought impact assessments and advocacy for large-scale responses. Additionally, the yield data contributed to an integrated region-wide assessment that combined household survey data and remote-sensing forecasts, improving the accuracy of damage and loss estimates.

Tools such as WFP's Economic Explorer[186] and FAO's online FPMA[187] help in predicting and tracking market prices, supporting early warning and better disaster preparedness.[188] These can help farmers in monitoring market conditions and obtaining alerts on price spikes that threaten food security. The FPMA tool offers weekly and monthly updates to over 2 500 domestic price series across 120 countries and 89 international food and agricultural input reference prices. This enables market participants to analyse trends, helps policymakers design effective interventions, and offers researchers access to vast amounts of data about food market dynamics. The integration of the United Nations Sustainable Development Goal 2.c.1 price anomaly indicator within the FPMA tool allows governments to monitor abnormal price fluctuations that could undermine food affordability. The FPMA tool fosters informed decision-making (by providing digitalized data and enhancing accessibility through APIs), strengthens food security and enhances the resilience of global and local food systems.

Beyond crop yields and price data, advances in the application of predictive analytics occur also for other areas, such as meteorological and hydrological hazards. Flood Hub[189] and Flood Forecasting[190] models from Google, for example, are tools under development that support flood predictions in ungauged watersheds, fostering more quality data generation.[191]

Near-real-time impact assessment

Decision-makers need quick, reliable and granular data on various dimensions of the hazard-related impacts to inform timely and impactful emergency response and recovery frameworks. Many challenges arise when these dimensions are applied to the agrifood sector. Risk and impact analysis requires a coherent understanding of biophysical and socioeconomic factors, which is often missing, leading to incomplete assessments, particularly for impact pathways and post-hazard needs of affected communities.

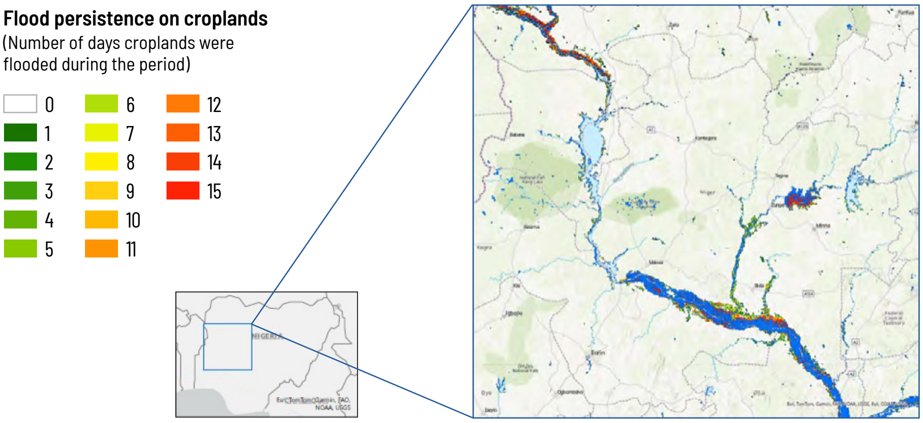
However, data is often incomplete and fragmented. Lack of data literacy and accessibility also hinders the uptake of existing information systems. Adoption is also limited when data comes late, after critical decisions such as appeals and resource allocations have been made, or when the data is not granular at the decision-making level (administrative level, population, livelihood profile). Additionally, difficulties in accessing affected areas and populations result in expensive and delayed data collection that does not align well with decision-making needs. To overcome these challenges, WFP has developed the Platform for Real-Time Impact and Situation Monitoring (PRISM).[192] PRISM integrates layers of vulnerability data to support the analysis of climate hazard impacts on food security, ensuring that the most vulnerable populations exposed to hazard-induced disasters are prioritized.

PRISM makes use of AI models to analyse historical weather data, satellite imagery, and real-time meteorological inputs, from sensors and IoT devices, to forecast weather events and to provide early warning alerts. Post-disaster damage assessments can be done quickly using satellite and drone imagery, combined with other socioeconomic data sources as seen in Myanmar and the Philippines.[193]

In collaboration with Google Research, WFP has developed SKAI, an AI and satellite imagery application to enable real-time insights and knowledge for effective decision-making in disaster response.[194] Fusing cutting-edge

FIGURE 29

VISUALIZATION EXAMPLE FROM EVENTS VISUALIZATION IN EMERGENCIES, SHOWING FLOOD PERSISTENCE ACROSS CROPLAND IN TARABA STATE, NIGERIA, OCTOBER 2024



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.
Source: Authors' own elaboration based on FAO. n.d. DIEM event viewer. [Accessed on 1 August 2025]. https://data-in-emergencies.fao.org/pages/diem_eve.

ML algorithms and vast satellite data, SKAI empowers organizations to make data-driven decisions (for example rapid building damage assessment, situational awareness and resource allocation), with precision and speed. This technology can be 13 times faster and 77 percent cheaper in near real-time post-disaster building damage assessment operational situations and has been used in disaster response during the Türkiye and Syrian Arab Republic earthquake (2023), Hurricane Ian (2022) and the Pakistan floods (2022).[195]

FAO's WaPOR is a platform hosting an innovative near-real-time database of satellite data that support disaster impact assessment.[196] The WaPOR platform provides timely, high-resolution, and spatially comprehensive data that is useful for pre-disaster risk mapping, real-time monitoring, damage assessment, environmental impact evaluation, humanitarian assistance planning and long-term recovery. [197]

The Events Visualization in Emergencies (EVE) system, developed in the Data in Emergencies programme uses satellite-derived and open-access data for the humanitarian sector.[198] EVE's open-access data approach is complemented by adherence to international Office for the Coordination of Humanitarian Affairs (OCHA) place codes, facilitating direct integration into humanitarian contexts and data workflows. Covering several countries (approximately 40 as of December 2024), with the flexibility to include additional countries during rainy seasons or at risk of flooding, EVE provides insights into flood events at both the granular and regional levels (see FIGURE 29). These insights empower organizations to make informed decisions quickly and accurately by offering intuitive interfaces and actionable information tailored to the fast-paced needs of emergency contexts.

Open-access data approach by EVE ensures scientific reliability while maintaining transparency and integration with other systems. EVE data sources include: Visible Infrared Imaging Radiometer Suite (VIIRS), which delivers daily, global and near real-time flood detection at 375-metre resolution;[199] European Space Agency (ESA) WorldCover, which identifies land cover types such as cropland, enabling targeted impact assessments with 10-metre resolution;[200] and population density and subnational administrative boundaries, which provide population exposure estimates and ensure data alignment with standards for emergency coordination (e.g. OCHA place codes).

EVE also uses an integrated technology stack for processing and analysis. This includes Google Earth Engine, which harnesses Google's cloud-based computational infrastructure to support large-scale geospatial analysis and perform complex geoprocessing operations efficiently. It enables EVE to process massive datasets rapidly. Python is used for data engineering and statistical processing, while ArcGIS Online provides intuitive, interactive dashboards for effective visualization.

EVE is versatile and tailored to meet the needs of diverse users. It provides an initial understanding of flood impacts on agriculture, helping government agencies, international organizations and NGOs to frame and triangulate field assessments and guide operations. EVE's user-friendly dashboards enable the exploration of flood dynamics over time and space, at scales ranging from multicountry regions to administrative levels 1 and 2. Since becoming operational in September 2024, EVE's outputs have significantly contributed to disaster response and long-term planning by FAO and other partners.

Linking early warning to anticipatory action

EWS are increasingly improving at predicting hazards threatening livelihoods and food security. This can help deliver finance for protecting livelihoods from hazard impacts, therefore speeding resilience-building. Innovative applications of EWS data are under development to meet this goal. Mobile technology can enable rapid identification of at-risk populations and deliver targeted warnings, amplifying the reach and effectiveness of preparedness efforts, for example as was the case in Bangladesh and Nepal.[201]

FAO provides technical support to countries for the development of sound trigger mechanisms for anticipatory action, leveraging the most advanced

SERBIA
View of drone flying over green wheat field in spring.
© iStock/Jevtic

technologies and promoting participatory and context-specific approaches. For example, in Somalia,[202] El Niño-induced flooding during the 2023 Deyr rainy season (October–December) affected an estimated 2.48 million people. Informed by an evidence-based EWS, primarily through the Somalia Water and Land Information Management Project's (SWALIM) flood model, in June 2023 FAO delivered anticipatory actions in partnership with the national government and humanitarian actors. Anticipatory actions included timely early-warning information, investments in flood defence infrastructure, prepositioning of sandbags, and coordination of evacuation and contingency planning with governments and local communities in key areas along the Shabelle and Juba Rivers. Ninety percent of at-risk populations were evacuated on time and river embankment rehabilitation in Beletweyne district held back flood waters for up to one week, enabling communities to move safely.

Innovative digital solutions are also needed to better target the at-risk vulnerable households, to speed up delivery and improve assessment prediction accuracy (for instance, the EVE tool presented earlier in this chapter could be used to assess flood prediction accuracy through satellite data).

BUILDING RESILIENCE THROUGH DIGITAL INNOVATION

Digital technologies can provide effective, timely, appropriate and sufficient support to farmers, assisting them in avoiding poverty and food insecurity. Indeed, these tools facilitate access to critical provisions, supporting risk transfer, reducing impact and improving coverage. They also increase livelihood resilience and improve social cohesion by fostering community relationships.

Agricultural insurance innovation

Agricultural insurance is a strong modality for providing safety nets for farmers.[203,204] Digital tools play a fundamental role in agricultural insurance, particularly in risk index insurance and in providing affordable products and services to individual farmers. By creating more fine-tuned risk indexes, lowering administrative costs, reducing human error and providing more objective assessments of damage, digital solutions reduce premium costs of agricultural insurance – a significant limiting factor for farmers. Digital technologies are also being leveraged for financial education and knowledge transfer, as well as for information provision on DRR and climate-resilient farming practices and more efficient use of agricultural inputs and seed choices. Using mobile money channels to digitize client registration, claim upload, and payout deliveries can strongly reduce the cost and time associated with these processes. This is particularly critical when it comes to expanding coverage among clients from rural areas.

The use of automated algorithms to assess the risk profiles of different subsegments of farming populations increasingly supports the provision of up-to-date, granular and precise data on small-scale farmers (e.g. in terms of their income flows, financial needs and value chain dynamics), putting private insurers in a position to engage with the agricultural sector. By leveraging a wide range of both quantitative and qualitative data points – such as satellite imagery of farms or interviews with neighbours – automated risk scoring systems can generate detailed profiles of potential clients. This reduces the risk for private insurers when providing coverage to these actors and helps lower premium costs.

The use of digital insurance technology (insurtech) in the agricultural sector carries the risk of widening the digital divide and further marginalizing those who, due to sociocultural and regulatory constraints, face greater barriers in accessing and using digital tools. In many developing countries, for example, rural women encounter significantly more obstacles than men in using mobile money services, owing to sociocultural expectations, lack of essential identification, and lower levels of digital literacy. As a result, efforts to expand agri-insurance coverage through Insurtech may inadvertently lead to further financial exclusion, with male farmers becoming the primary beneficiaries of innovation. It is therefore essential to consider these structural constraints when designing, delivering and evaluating digital insurance products, and to ensure equitable access for all.

Founded in 2015 in Kenya, Pula Insurance Advisors is an insurtech company that focuses on developing digital parametric insurance products for small-scale farmers in climate shocks-affected contexts.[205] Pula operates by establishing end-to-end partnerships with a wide range of stakeholders, such as insurance companies, agricultural technology companies, commercial banks, government entities, development agencies, agri-input dealers and other providers. It aims at fostering collaboration to bridge critical demand- and supply-side gaps that normally prevent insurance for smallholder farmers. Pula is present in 13 countries in sub-Saharan Africa. In 2021, the company began implementing its model in Cuba, Indonesia, Pakistan and the Philippines.

Pula employs several instruments to achieve a balance between profitability and affordability. First, it uses mobile-based registration systems (both app- and SMS-enabled) to register new users in a rapid and efficient manner. Second, it leverages automated learning algorithms that can group together agricultural producers whose farms share similar features. Third, Pula uses digital tools to automatically evaluate reimbursement claims from the field, greatly increasing efficiency and ensuring that payout claims are settled and delivered to the farmers within 5–7 weeks. Compared to most existing index-based insurance schemes, this represents a significantly short settlement period.

As of mid-2023, Pula had insured 9.1 million farmers, for a gross premium of USD 69.1 million, ensuring coverage for approximately 4.4 million hectares of land across 17 countries. Pula's coverage resulted in payouts being delivered to 755 000 farmers as of mid-2023, with a total of USD 27.1 million in claims being disbursed. Pula's approach of combining insurance with agricultural advice has shown impressive outcomes, with clients registering increased investments in their farms by up to 16 percent and significant yield improvements of up to 30 percent.

Livestock risk management tools

Large datasets support research, policy tracking, planning and decision-making, although turning data into risk-informed decision-making requires significant amounts of analysis and modelling. The Livestock Investment Rapid Appraisal (LIRA) aims to improve cost-efficient decision-making and to support wider applications at the institutional level.

The livestock sector is vital for global agrifood systems, livelihoods and economies, but it is highly vulnerable to disasters, such as droughts, disease outbreaks and extreme weather. These events result in livestock mortality, reduced productivity and long-term economic damage, impacting household incomes and food availability. However, stakeholders often lack tools and data to assess risks and implement effective interventions. Without a clear assessment of impacts and benefits, decision-makers cannot optimize resource allocation, and private investment in resilience-building measures remains limited.

LIRA assessed the loss and damage of the 2016/2017 drought in Somalia. In 2017, after three consecutive seasons of insufficient rainfall, Somalia declared a national disaster. The World Bank, the United Nations, and the European Union conducted Drought Impact and Needs Assessments (DINAs), which considered only the drought year. In contrast to the DINAs, the LIRA assessment uses a modelling framework that compares a drought scenario with a no-drought scenario, based on pre-drought livestock population and production parameters. It covers five post-drought years and therefore accounts for longer-term losses resulting from the immediate loss and damage experienced during the drought year.

Risk reduction can also be conducted through anticipatory peste des petits ruminants (PPR) (also known as sheep and goat plague) vaccination. PPR is a highly contagious viral disease that can cause high morbidity and mortality in small ruminants such as sheep and goats. The disease can cause significant economic losses, therefore vaccination is vital to respond to PPR epidemic risks. The cost and benefit assessment of anticipatory PPR vaccination has been based on the baseline scenario from the previous ex-post loss and damage assessment. In a normal year, a sheep/goat is estimated to generate a return of around USD 21. In the case of an outbreak of PPR, annual returns are estimated to decline by around 40 percent, mostly due to increased mortality.

PPR vaccination has an average benefit–cost ratio (BCR) of 16, indicating a highly attractive investment. It breaks even – achieving a BCR of 1 – at a vaccination cost of USD 3.7 per animal, an expected loss of USD 0.60 per animal, or a disease risk of 3.6 percent. These break-even thresholds strongly suggest that vaccinating goats against PPR is highly likely to cover its costs and remains economically viable even if livestock keepers must bear the expense themselves.[206]

LIRA empowers stakeholders to make informed decisions, mitigating risks and fostering sustainable development. The potential of LIRA could be expanded by increasing the scope and volume of data available, as well as by including metrics for livelihood and environmental impacts. In this regard, the Livestock Intervention Coordination System (LICS) offers information that can further inform LIRA.

Integration with social protection systems

Social protection comprises a set of policies and programmes that addresses economic, environmental, and social vulnerabilities by protecting and promoting livelihoods. Through its preventive, protective, and transformative functions and the delivery of cash and/or in-kind support, social protection helps tackle vulnerability to poverty and food insecurity, to avert losses of income, livelihoods and assets, and to build resilience against disasters and crises. It also supports asset accumulation, invests in human capital, provides a buffer for the uptake of climate-smart agricultural practices and climate adaptation activities, stabilizes incomes and ensures access to credit.

Traditionally, social protection systems have been designed to address risks faced by individuals and households, but recent efforts are devoted to leveraging them for reducing or managing covariate shocks. Covariate shocks are those affecting a wide number of households in a specific geographic area, such as drought, floods and conflict. In this latter case, covariate shocks are called "shock responsive" or "adaptive" social protection systems,[b] which facilitate and complement DRM interventions.

Utilizing social protection systems to complement DRM efforts involves leveraging specific components of the delivery chain, including data, digital, communication and delivery solutions. For instance, social protection management information systems (i.e. social or beneficiary registries) can be overlayed with shock-related risk and vulnerability datasets, or livelihood-specific information from farmer registries, to improve recipient identification and target interventions.

Finally, social protection payment and service systems provide a key avenue to complement or channel DRM interventions. Cash assistance from social protection systems is often disbursed through a combination of channels, including physical cash or electronic payments (e.g. mobile wallets and payments). Kenya's M-Pesa facilitated quick and efficient relief payment of USD 7 million to 1.1 million beneficiaries during the 2017 drought. An example of the reaching scale of these systems is the Social Cash Transfer Programme by the Government of Malawi. In 2022 it provided cash support to 74 000 households ahead of a particularly poor lean season.[207] Digital payments help mitigate risks associated with physical cash disbursements and significantly reduce transaction costs. In Kenya, mobile wallets enable beneficiaries to safely and securely access their funds for immediate use on basic needs. They also allow for real-time recipient verification and provide an audit trail that helps reduce corruption risks and inefficiencies during implementation.

Supporting improved disaster impact data collection

Drones and UAVs are emerging as an excellent tool for data collection for DRR, together with high-resolution satellite imagery. The range

b Adaptive social protection systems typically integrate components of human capital development, disaster risk management, and climate adaptation and mitigation. Shock-responsive social protection is generally considered a subcomponent of adaptive social protection, with a primary focus on the linkages between social protection and disaster risk management. In some contexts, the two terms are used interchangeably.

of applications of drones in agriculture is extensive.[208] At the meso-level, governments (national, subnational and supporting agencies) are finding innovative applications for drones/UAVs in disaster impact assessment. UAVs have been crucial in providing rapid, high-resolution and insightful data that helps in hazard mapping, damage assessment, planning interventions, surveillance and monitoring. The use of multispectral sensors on drones can capture plant health and detect disease, supporting both advisory services and data collection.

For example, in 2014, FAO trained Libyan and Ethiopian policymakers and experts on the theory and practice of remote sensing (including UAVs) application on water infrastructure management. Trainees learned to operate drones and interpret and apply related data for monitoring and maintenance of critical water infrastructure, as well as spraying and multispectral mapping. These initiatives had relevant impacts. Drones enable rapid and precise monitoring of large areas, reducing the time and labour required for conventional methods. High-resolution data supported targeted interventions, minimizing resource waste while improving yields and infrastructure resilience. Despite these advances, challenges such as regulatory barriers, costs and integration into existing DRR frameworks remain.

Other examples of WaPOR's role in such activities are taken from the Syrian Arab Republic and the Sudan.[209] In 2019, the WaPOR supported the damage assessment of the Syrian Arab Republic's irrigation infrastructure (dams, pumping stations and irrigation systems) due to the ongoing conflict. By analysing plant growth and water usage through WaPOR's Actual Evapotranspiration (AETI) layer, areas where irrigation infrastructure had survived were identified. In semi-arid regions like Deir Ez-Zor, AETI was effective in detecting irrigation activity by tracking water loss via evaporation, transpiration and interception, providing vital information on the state of agricultural systems. Understanding the impact of conflict on national agricultural investments was essential for the Ministry of Water Resources to assess damage and guide its reconstruction and resource mobilization efforts.

Similarly, in the Sudan, WaPOR data was used to assess the 2023 growing season and compare the season's average with the previous five years, aiming to estimate the impact of the ongoing conflict on agricultural production.[203] The assessment revealed a 51 percent reduction in cultivated areas at the start of the season compared to previous years, mainly due to disruptions in markets and financing mechanisms that hindered farmers' access to agricultural inputs. WaPOR data was used to inform an agricultural seeds distribution programme, enabling more farmers to plant on time for the growing season. This demonstrates that remote sensing data, such as WaPOR, can provide co-benefits in monitoring the impact of conflicts on agriculture and supporting humanitarian responses. ■

3.3 MAINSTREAMING DIGITAL SOLUTIONS AT SCALE

To fully employ digital solutions for DRR in agriculture, a shift is necessary in how we approach and address agricultural risk. Digital solutions for DRR support the transformation of agrifood systems. However, to maximize their potential, technological innovations and tools need to be embedded in digital agricultural policies, strategies and plans supported by the necessary finance for implementation. Moreover, to be truly people-centred and transformational, digital solutions for DRR must be affordable, accessible and tailored to the needs of the most vulnerable farmers.

Bold actions, policies, and the right regulations and investments are integral to accelerating the transformation necessary. This requires significant investments in key building blocks such as data governance, digital infrastructure, digital applications and services, enabling policy and environment, capacity development and institutionalization, and partnerships and finance. Embedding HCD principles in digital tools for agriculture is key. HCD not only creates more effective tools but also builds long-term capacity for innovation and empowers different actors to efficiently address agricultural challenges.

ENABLING ENVIRONMENT AND INFRASTRUCTURE

Data governance and interoperability

Effective data governance is essential to leveraging digital innovation. To support the integration of diverse datasets across sectors and facilitate data sharing, risk-related data must be accurate, accessible and interoperable. The development of interoperable systems, such as the EU Integrated and Control Management System (IACS), and the adoption of standardized protocols can streamline data sharing, reduce fragmentation and support comprehensive risk assessments. For example, India's Digital Public Infrastructure for Agriculture integrates weather, soil and crop data in EWS. Indonesia's One Disaster Data Initiative streamlines data from various sources, including data management and statistics on DRM and financing of related activities. The Philippines' National DRR and Management Council (NDRRMC) uses a data-driven approach to supporting multi-sectoral disaster response.

Lack of reliable data hinders effective DRR efforts; therefore, strong data governance is essential to sustain risk-informed and data-driven policy interventions and coordinated response. Data governance encompasses technical, policy and regulatory frameworks to manage data throughout its value cycle – from creation to deletion – and across policy domains. However, in many countries, the absence of standardized protocols for data collection, sharing and value creation limits the ability to generate meaningful insights from data.

For disaster tracking systems to succeed, adopting a common framework is necessary. This includes scientifically agreed hazard definitions and taxonomies (such as those developed by the International Science Council), and well-tested post-disaster assessment methodologies (e.g. DaLa and PDNA). Disaster tracking systems should also be customizable to reflect local specificities on asset categories, data contributors, unit of analysis, currency or languages.

Using APIs, geospatial layers of vulnerability and exposure can be added to disaster impact data, permitting new directions of analysis, enhanced data integration and processing and visualization functionalities. Data visualization options to showcase impact, such as per sector, hazard and disaster events, can help summarize impacts and better communicate dimensions, such as disruption in production or access to services, which are not always visible when using monetary valuation of losses. Furthermore, a mobile-first software system with advanced geospatial data collection and analysis functionalities can support users in digitalizing data collection, while facilitating workflows for data sharing, validation and coordination.

The DELTA Resilience system developed by UNDRR aims to fill this gap by equipping local governments, sectoral and specialized agencies to collect and share better data related to impact on people, assets and services under their jurisdiction. DELTA Resilience system impact data also helps in measuring the effectiveness of DRR, climate adaptation and losses and damages. Showcasing the value of better data for better action is meant to encourage governments to invest in a disaster tracking system by enhancing data ecosystem and governance, institutional mechanisms and operational procedures.

Digital infrastructure requirements

A robust digital infrastructure can provide the foundation for effective DRR. This includes energy solutions, connectivity, devices and efforts to address socioeconomic challenges to co-create digital solutions and foster innovation. Ensuring digital tools and content are context-specific, linguistically relevant and economically viable is crucial for bridging the digital divide, including the digital divide for women.[210] Despite significant progress in global connectivity, 2.6 billion people remain offline. Of these, an estimated 38 percent live within mobile broadband coverage but do not use it, while 5 percent are still not covered by mobile broadband at all.

People with access to digital resources can benefit from powerful services and opportunities unavailable to those who remain offline. To address this challenge, Farm Radio International in sub-Saharan Africa combines radio broadcasts with mobile and interactive voice response systems to reach farmers with limited internet access in remote areas. This ensures the timely dissemination of localized weather advisories and emergency alerts, enabling them to respond quickly and effectively to potential disasters.

Policy frameworks and strategies

Mainstreaming digital solutions in both agricultural and institutional DRR strategies fosters agrifood system transformation. For example, national digital agriculture strategies (DAS) like the one in Madagascar pave the way for the sector's transformation by integrating technology, data and innovation. Supported by FAO, the Digital Transformation Strategy for Agriculture in Madagascar 2024–2028 aims to improve food security and farmers' incomes, while developing the country's economy through digital technologies. Its vision is to transform Malagasy agriculture through people-centred digital technologies such as satellite imagery, mobile applications and data analytics. These tools seek to empower farmers with real-time information for better decision-making, optimize supply chain logistics, and improve access to markets and financial services. This initiative is particularly vital in Madagascar, where agriculture is central to the local economy and livelihoods, yet is frequently threatened by natural hazard-induced disasters and climate variability

DAS can support centralization of diverse datasets and establish interoperable systems to ensure comprehensive and seamless data sharing for agrifood and DRR. In Rwanda, integrating DRR into the national DAS aims to both address immediate disaster impacts and strengthen the long-term resilience of agrifood systems. The development of DAS, supported by FAO (such as Rwanda ICT4AG 2016–2020 and the National Digital Agriculture Strategy 2021–2026), marks a significant step in leveraging emerging technologies to improve agricultural productivity and sustainability. By aligning the DAS with the Strategic Plan for Agrifood Systems Transformation 2024–2029 (PSTA5), Rwanda is taking a forward-looking approach to agricultural transformation, incorporating DRR. DAS underscores Rwanda's commitment to creating a resilient, sustainable agriculture sector that can withstand shocks and stresses such as those induced by climate and market fluctuations. Through digital tools such as data analytics, mobile apps and precision agriculture, farmers can access real-time weather, soil health and crop data. DAS focuses on four key areas: (1) service digitalization to promote interoperability and agricultural technology; (2) data-driven decision-making through agricultural data governance; (3) digital competence development; and (4) the adoption of emerging technologies for agricultural traceability, supply chain automation and smart agriculture.

DAS can also inform the development of evidence-based policies, standards and regulations for data management, as well as digital platforms for disaster insurance, subsidies, compensation and EWS. They can provide a clear roadmap for developing digital solutions for DRR in agriculture, based on the assessment of needs and the digital readiness of the country. The FAO-ITU DAS guide provides a framework to assist countries in shaping their national DAS and identifying sustainable digital solutions.

Financing and partnership models

Specific resource allocation and business models are important for ensuring the long-term sustainability of digital solutions for DRR. Funding models through public–private partnerships, donor funding or blended finance models, and securing cost-effective pricing models that suit agriculture stakeholders will ensure accessibility and scalability of such digital solutions. India's Digital Agriculture Mission has committed public funding and, in partnership with the private sector, delivers digital services to the agriculture sector. In South Africa, Kuronga offers a tiered subscription model for farmers and applies AI-based grading tools to help them meet market needs and quality standards. Pula, the microinsurance company, leverages technology, data analytics and AI to develop innovative climate insurance solutions bundled with agricultural inputs. Pay-as-you-go models for digital agricultural services, implemented in partnership with local cooperatives, have also proven successful in various contexts.

Effective partnerships are crucial to reducing the digital infrastructure gap in rural areas. In many countries, multisectoral public–private collaborations with the private sector, academia, civil society and technology providers effectively supported rural communities in moving towards a digital economy. It also significantly strengthens data and knowledge sharing, interoperability and seamless service delivery for DRR. The partnership between FAO and Google exemplifies how digital tools like the Google Earth Engine (GEE) can transform DRR in agriculture.

The FAO–Google Earth Engine Partnership (GEEP) has launched dashboards to track submissions to United Nations Framework Convention on Climate Change (UNFCCC) and to monitor deforestation-free commodity value chains. These tools leverage GEEP's processing power to provide real-time data, aiding countries in meeting their climate commitments. Over 500 people in Ethiopia, Viet Nam, and the Plurinational State of Bolivia have been trained in using GEEP through workshops, webinars and e-learning courses, enhancing capacities in climate monitoring and environmental protection. GEEP has also provided 1 500 people, including farmers, local small- and medium-sized enterprises (SMEs), and vulnerable communities, with access to critical data and tools for managing agricultural risks. This partnership increased the use of geospatial analysis in FAO projects, contributing to better production, nutrition, environment and life. It also underscores the importance of effective collaboration with big technology companies in bridging the digital infrastructure gap and enhancing resilience.

India's rural connectivity revolution has seen partnerships between government and telecommunication companies to extend coverage and empower communities. For example, the Grameen Foundation has helped rural communities access mobile money and other financial services. In many African countries, M-Pesa supported financial inclusion through partnerships with companies and financial institutions. M-Pesa has also partnered with Microsoft to develop digital skills for micro-, small- and medium-sized enterprises (MSMEs). In Rwanda, the government-supported platform e-Soko disseminates real-time market prices and weather updates via SMS and web portals. Meanwhile, the Private Sector Alliance for Disaster Resilient Societies (ARISE) partnership has also enabled the integration of the private sector into national DRR efforts.

IMPLEMENTATION PATHWAYS AND COUNTRY EXPERIENCES

Integrated systems and platforms

The Philippines is taking a transformational shift towards ecosystem-based governance, integrating scientific data and interoperable systems for better decision-making and enforcement. In August 2024, bathymetric data were incorporated into the Integrated Marine Environment Monitoring System (IMEMS), redefining municipal waters based on ecological realities. This shift aligns with broader environmental policies emphasizing data interoperability and technology. The Philippine Ecosystem and Natural Capital Accounting System (PENCAS) Act supports this by standardizing environmental and economic data. Innovative tools, in particular rapid visualization methods such as heat maps, are developed to respond quickly to complex data, such as critical insights into coral reef health, fishing activity and enforcement gaps.

An integrated solution that connects data visualization and resource management was designed to allow fishers to access real-time data, such as depth and ecological characteristics, enhancing their fishing efficiency and environmental knowledge without additional costs. This solution includes layers like marine protected areas and legal boundaries to provide comprehensive environmental information. The solution integrates concepts developed in the environmental witness model,[211] enabling users to report pain points directly in real time. These can range from perceived violations of environmental laws, maritime accidents, safety hazards to environmental characteristics (e.g. algal blooms) and heat-related observations (e.g. coral bleaching). This aims at mitigating, for example, illegal, unreported and unregulated fishing, alongside building communities of best practices through the concept of social reporting and whistleblowing. The system also enables managers to visualize resource usage through heat maps, facilitating better management decisions. The platform's data can be enriched by the ability of the API to import contributions from researchers, government agencies and ongoing fieldwork, ensuring comprehensive and up-to-date information. For aggregating data into the system from specialized tasks like predictive modelling and ecosystem niche modelling, ArcGIS is recommended due to its advanced capabilities in ML for feature classification and geostatistical forecasting. ArcGIS also offers valuable communication tools like story maps and mobile apps to create a more connected and responsive fisheries management systems. The data collection process and flow are designed to follow a cycle of validation and approval as defined in PENCAS. After methodology standardization and validation, data can be processed at scale using ML resources.

While three systems were considered – ArcGIS by ESRI, Quantum GIS (QGIS) and GEOVS from SRT – GEOVS was identified as the most suitable platform for integrating real-time environmental data into a unified framework. GEOVS enables natural resource management agencies to make informed decisions based on real-time insights. However, it requires ongoing scaling based on project priorities, as well as extended deployment to enable customized and context-specific features. This highlights that digital solutions should be context specific, and that investing in them is necessary for creating integrated solutions, alongside investments in capacity development along the entry points of the system.

A pathway for deploying sensor-equipped buoys to enhance the Philippines' marine resource management has been formulated too. These buoys are equipped with tools such as transponders, cameras, acoustic sensors and environmental monitoring instruments. They provide continuous real-time data on marine conditions and activities. These buoys can be integrated into the IMEMS GEOVS system and provide actionable insights for decision-makers and improve enforcement, biodiversity protection and the sustainability of marine resources.

GEOVS also aims to enhance socioeconomic resilience by incorporating risk reduction, disaster response and recovery systems. Its three components include using real-time monitoring and geospatial tools to identify environmental disruptions and trigger local response protocols; allowing fishers to document and report post-disaster damages through a mobile interface, linking data to insurance and aid programmes; and engaging communities in data-sharing and disaster preparedness through app notifications and real-time updates. This approach ensures that vulnerable fishing communities have access to recovery resources, turning passive monitoring into proactive resource management, and reinforcing national food security and socioeconomic stability.

Capacity development and digital literacy

Moreover, human capital critically enables digital transformation in DRR. Public institutions and advisory services can drive digital innovation by investing in digital DRR capacity development (e.g. skills development, digital and financial literacy, livelihood diversification with a focus on women, youth and equitable access) to strengthen individual, institutional and community resilience. In Barbados, FAO is strengthening the capacity of extension services through the introduction of precision agriculture to improve crops. The development of a decision support system provides accurate data to inform critical crop management decisions. It offers precise recommendations on input use – including application rates, timing and safety intervals – along with other essential guidelines to enhance nutrient and pest management efficiency and reduce food safety risks.

Enhanced digital capabilities also improve decision-making through data-driven insights and scenario planning. For example, in Grenada, FAO supported the creation of a drone mapping and GIS team within the Ministry of Agriculture and Lands, Fisheries and Cooperatives. This allows for better utilization of agriculture data collection and planning techniques, for acquiring updated spatial information for farmers and for better communication with communities dealing with flooding. In India, the National Disaster Management Authority (NDMA) trains and equips officials, stakeholders and the community on disaster response. Building the capacity and skills of the public sector to effectively leverage data, extract actionable intelligence and strengthen data-driven policy interventions is crucial for enhancing DRR.

Education equips farmers with the necessary knowledge and skills to implement effective DRR practices and measures. Farmers learn about practices (e.g. sustainable farming techniques, soil conservation, water management and crop diversification) that mitigate the effects of disasters and ensure productivity standards and livelihood protection. Leveraging human capital in rural communities is therefore crucial. For example, the Bangladesh Cyclone Preparedness Programme (CPP) has trained 76 thousand volunteers, 50 percent of them women, to disseminate early warning and coordinate response to cyclones.

Moreover, agricultural education fosters a better understanding of risk information, including climate services and EWS and disaster preparedness plans. Farmers are trained to recognize signs of impending disasters and take proactive measures to safeguard their crops and livestock. This knowledge not only reduces the immediate impact of disasters but also aids in quicker recovery and long-term sustainability. By promoting community-based approaches and encouraging collaboration among farmers, agricultural education strengthens the overall resilience of agricultural communities.

Mobile apps, online platforms and digital advisory services offer tailored advice and training, helping farmers adopt good practices and innovative techniques. Digital solutions also facilitate farmers' access to markets, buyers, and financial services and institutions. This improves their ability to secure fair prices and obtain necessary credit and insurance. An effective example is that of Kenya's Kilimo Salama project, which provides climate risk insurance to farmers through mobile phones. Integrating digital solutions into agriculture also empowers farmers to build sustainable livelihoods and better withstand the impacts of climate extremes. In Uganda, FAO is helping women in remote rural areas without access to the internet and smart devices to inform and inspire rural communities to drive social change. Using Amplio Talking Book as a technology, FAO sensitized around 8 000 people on women's land rights and land management in the West Nile region.

Similarly, FAO's Virtual Learning Centers (VLC) strengthen rural communities to be better prepared for animal disease outbreaks. VLCs are virtual hubs that develop and deliver online and blended courses for professionals supporting farmers and rural communities. They are crucial in building preparedness and response capacities for animal health emergencies. The courses on transboundary animal diseases (TADs) can be quickly adapted and translated to train large audiences at low cost.

The VLCs use decentralized and innovative approaches and methodologies to train professionals in remote areas that otherwise would not have access to similar training opportunities. In the Pacific Islands, the VLCs have delivered multiple courses for veterinary paraprofessionals (VPPs) and community health workers (CHW), focusing on empowering women, helping them to become One Health leaders in their communities, and training them on how to provide community-responsive services. This has provided more effective community-driven health and animal disease responses.

HUMAN-CENTRED APPROACHES AND FUTURE DIRECTIONS

Finally, adopting a human-centred design approach helps improve usability and engage farmers and stakeholders in developing digital agriculture solutions. For example, the Consultative Group on International Agricultural Research (CGIAR) has made efforts in integrating HCD to reduce adoption risks, align solutions with real needs and enhance user satisfaction. The redesign of the feedback mechanism for triadic comparison of technology options (tricot) allows farmers to test new crop varieties directly on their farms and provide feedback on their preferences and observations. Similarly, the Artemis project focuses on AI-supported digital phenotyping for crop breeding programmes across Africa. These initiatives have proven that HCD is not only an effective tool but also builds long-term capacity for innovation, empowering farmers, researchers and communities to effectively face agricultural challenges.

Human-centred design principles

HCD offers a solution by prioritizing empathy, inclusivity and iterative design to deeply understand user needs and integrate them into every stage of development. The HCD process follows five key stages: scoping, exploration, creation, validation and implementation. Scoping defines the problem and goals. Exploration focuses on understanding user contexts and constraints. Creation involves developing prototypes based on insights, followed by validation through user testing and iterative refinements. Implementation ensures solutions are deployed effectively. Several successful digital agriculture solutions were co-designed with farmers to understand their challenges, preferences and local contexts.

For organizations to effectively implement HCD, several foundational elements must be in place. First, institutional commitment and leadership buy-in are necessary to prioritize HCD across projects and workflows. Leaders are crucial in fostering a culture of innovation and user-centric thinking. Second, capacity building is essential to equip teams with the necessary HCD skills and methodologies. Training workshops, hands-on design sprints and regular knowledge-sharing sessions can build expertise across teams. Third, cross-disciplinary collaboration is key. HCD requires teams to include designers, developers, domain experts and end-users working together throughout the design process. Fourth, organizations must establish iterative feedback loops to continuously gather and act on user feedback during each phase of a project's lifecycle. This involves investing in tools and systems for usability testing, prototyping and iterative refinement with multiple tools available. Finally, sufficient resources and infrastructure must be allocated for prototyping, user research, and long-term monitoring and evaluation. Without these foundational elements, HCD efforts risk being superficial and ineffective.

HCD prioritizes user needs, iterative improvement and context-specific design. It ensures that digital solutions for risk reduction are not only technically sound but also socially and culturally aligned with the users' realities. The iterative and community oriented nature of HCD fosters trust, enhances adoption, and ensures that digital innovations contribute meaningfully to resilience and sustainability in agriculture.

Human-centred design in practice

In Rwanda, the International Institute of Tropical Agriculture (IITA) and Viamo were interested in understanding the usability and user experience with a diet quality survey delivered through unstructured supplementary service data (USSD). A heuristic evaluation revealed significant usability barriers due to interface design flaws and inconsistent language translations. To address these issues, a usability lab was set up where participants completed the survey while being observed and interviewed. This revealed several challenges, including unclear instructions, language mismatches in messages and technical difficulties when navigating long questions on small screens. Key insights stated the need for clearer prompts, improved user control (e.g. the ability to undo mistakes) and simplified navigation. Adjustments included better communication between the survey platform and telecom providers to reduce system errors, as well as clearer instructions and question framing. These changes significantly improved survey completion rates from 58 to 70 percent, with women's completion rates increasing to 76 percent. Data quality also improved, demonstrating the tangible benefits of applying HCD principles to digital tools.

The SEED Hub was developed with the HCD approach. The platform was co-developed by CSI in collaboration with Rwanda's Ministry of Agriculture, the Department of Meteorology, and the Hector Kobbekaduwa Agrarian Research and Training Institute (HARTI). Local stakeholders contributed by populating the SEED Hub with context-specific information, ensuring it addressed local needs while leveraging existing institutional expertise. Capacity-building initiatives enabled organizations to maintain and update the platform. In addition, four workshops were conducted by the CSI team to train stakeholders on developing effective, user-friendly messages for farmers and on uploading information to the platform.

Zalo (a messaging platform providing farmers access to a 10-day Agro-Climatic Bulletin [ACB] in Viet Nam) provides another example.

To understand how farmers accessed and interacted with ACB through the messaging app, a usability test was conducted. The test involved guiding farmers through accessing ACB on their phones, completing navigation tasks, and providing feedback on accessibility, design and readability, comprehension and usefulness of the bulletin. The test uncovered issues such as difficulty locating ACB in messaging group chats, small fonts and dense text and confusion caused by technical terms. Farmers appreciated the ACB's role in reducing weather-related risks but preferred more actionable, specific recommendations and more frequent updates to match their decision-making and their needs in critical periods, including droughts or salinity intrusion. The usability testing also captured non-verbal cues or negative reactions, like lack of attention, disengagement and confusion, which farmers might not express verbally.

Future directions and emerging technologies

As we look to the future of digital solutions for DRR in agriculture, several emerging technologies and trends are poised to transform the landscape. The convergence of AI, IoT, blockchain, and advanced satellite technologies promises to create even more sophisticated and integrated risk management systems.

The next generation of digital DRR solutions will likely feature greater automation and predictive capabilities, with AI systems capable of autonomously detecting and responding to emerging threats. Edge computing will enable real-time data processing at the field level, reducing dependency on connectivity and enabling faster response times. Quantum computing may revolutionize our ability to process complex climate models and predict agricultural risks with unprecedented accuracy. However, it is important to recognize that AI and emerging technologies alone are not a panacea; effective digital DRR for agriculture requires human oversight of AI systems, risk informed governance and robust institutional frameworks that are aligned with international ethical AI guidelines, such as those outlined in the United Nations Educational, Scientific, and Cultural Organization's (UNESCO) *Recommendation on the Ethics of Artificial Intelligence*.[212] These are key to ensuring that technology is applied transparently, accountably and fairly, while respecting human rights.

Realizing this potential requires addressing several critical challenges. The digital divide remains a significant barrier, with many rural communities still lacking basic connectivity and digital literacy. Ensuring that advanced technologies benefit smallholder farmers and vulnerable communities will require continuous focus on accessibility, affordability and human-centred design.

Moreover, as digital systems become more integrated and autonomous, questions of data sovereignty, privacy and control become increasingly important. Establishing governance frameworks that protect farmers' rights while enabling innovation will be crucial for sustainable digital transformation in agriculture.

The journey towards fully digitalized agricultural DRR is ongoing, but the foundations laid today through innovative tools, accessible governance and enabling policies, and human-centred approaches are paving the way for more resilient and sustainable global agrifood systems. By continuing to prioritize the needs of farmers and vulnerable communities while responsibly embracing technological innovation, we can build agrifood systems that not only withstand shocks but are also capable of thriving in the face of mounting challenges of climate variability, biodiversity loss, pollution and environmental degradation. Now is the moment to act towards transforming risk into resilience and innovation into impact. ■

CANADA

Aerial view of damaged crops after record-breaking rainfall.
© iStock/shaunl

PART 4

CONCLUSION

CHARTING A PATH FORWARD FOR DISASTER RISK REDUCTION IN AGRICULTURE THROUGH DIGITAL INNOVATION

The convergence of escalating disaster impacts on agriculture and the emergence of transformative digital technologies offers a defining moment for global food security and rural livelihoods. The comprehensive analysis presented in this report reveals both the magnitude of the challenge and the opportunities for building resilient agrifood systems capable of adapting to the increasing impact of disaster risks. As the evidence demonstrates, disasters affecting agriculture have inflicted an estimated USD 3.26 trillion in losses over the past 33 years, with annual damages accelerating from USD 62 billion in the 1990s to over USD 200 billion in recent years. These figures, while significant in scale, only begin to capture the true extent of disaster impacts on agrifood systems and the communities that depend on them.

The complexity of disaster impacts on agriculture extends far beyond immediate production losses to encompass cascading effects through interconnected agrifood systems. The disruption of infrastructure, markets, financial services and ecosystem functions creates ripple effects that can persist for years after the initial event. These events affect prices, trade patterns and food security thousands of miles from the initial impact zone, underscoring a fundamental reality of our interconnected world: disasters affecting agriculture anywhere become food security challenges everywhere.

Climate driven changes intensify extreme weather events that gradually erode agricultural productivity. Rising temperatures, shifting precipitation patterns, and the increasing frequency of extreme weather events are pushing agricultural systems beyond their adaptive capacity. The intersection of climate extremes with existing vulnerabilities creates compound risks that current management approaches struggle to address. Simultaneous hazards can create complex emergencies that overwhelm conventional response mechanisms and lead to disproportionate impacts on food security and livelihoods.

The assessment of current monitoring and evaluation frameworks reveals significant limitations in our ability to capture the full spectrum of disaster impacts on agriculture. The Sendai Framework Monitor and PDNAs provide valuable standardized approaches, but they focus primarily on direct economic damage and loss and do not systematically account for indirect effects, non-economic values or longer-term consequences. The systematic exclusion of impacts on ecosystem services, cultural heritage, Indigenous knowledge systems, and differentiated effects on women creates a selective picture that can misguide policy decisions and resource allocation. These assessment gaps are compounded by limited country participation, inconsistent reporting, and substantial variations in data quality that undermine the reliability and comparability of global monitoring efforts.

The quantitative analysis of direct economic losses in crops and livestock reveals important patterns in the distribution of vulnerability and risk. Lower-middle-income countries suffer the highest relative losses at almost 5 percent of agricultural GDP, while Africa bears the highest regional burden at 7 percent of agricultural GDP, despite lower absolute losses. SIDS face disproportionate impacts relative to their size, reflecting their extreme vulnerability to climate shocks and limited adaptive capacity. These disparities reflect not merely differences in exposure to hazards but fundamental inequalities in infrastructure quality, institutional capacity, and resource availability for disaster risk reduction and response.

The nutritional dimension of disaster impacts in agriculture adds another layer of concern that extends beyond economic metrics. Production losses translate into significant nutritional shortfalls, which have the potential to disproportionately affect vulnerable populations, particularly women and children, and create long-term developmental consequences that extend far beyond immediate food shortages.

DIGITAL TECHNOLOGIES AS CATALYSTS FOR CHANGE

Against this backdrop of mounting challenges, digital technologies emerge as potential transformative tools for enhancing and complementing disaster risk management practices in agriculture. The proliferation of remote sensing capabilities, AI, IoT sensors, and mobile communication platforms creates unprecedented opportunities for understanding, predicting and responding to disasters. Early-warning systems demonstrate remarkable advances in combining multiple data sources with sophisticated analytics to provide actionable intelligence for anticipatory action. Digital advisory services are also successfully bridging critical information gaps that have long constrained smallholder farmers' ability to manage risks and optimize production. Platforms delivering soil health recommendations, water management guidance, and agrometeorological advisories directly to farmers' mobile devices demonstrate measurable impacts on agricultural productivity and resilience.

The integration of digital technologies into pest and disease monitoring systems also represents another area of transformative impact. FAMEWS demonstrates how combining mobile data collection, cloud-based analysis, and real-time mapping can enable rapid response to transboundary pest threats. By processing data from over 50 000 field scouting activities and 16 000 pheromone traps across more than 60 countries, FAMEWS provides the foundation for predictive models and targeted interventions that have reduced infestations and associated yield losses in multiple African countries.

Digital financial services, particularly mobile money and parametric insurance, are creating new pathways for risk transfer and recovery support that overcome current barriers of geography and infrastructure. The success of companies like Pula in providing affordable insurance to over 9 million smallholder farmers demonstrates how digital technologies can reduce administrative costs, improve claim processing efficiency and enable rapid payouts that help farmers recover from disasters. The integration of insurance with agricultural advisory services shows additional benefits, with clients increasing farm investments and achieving significant yield improvements.

However, the implementation experiences also reveal significant challenges and limitations that must be addressed for digital transformation to achieve its full potential. The digital divide remains a persistent barrier, with 2.6 billion people still offline globally and many more lacking the digital literacy, devices or financial resources to effectively utilize digital services. Rural areas, where most agricultural production occurs, face challenges in terms of limited connectivity, unreliable electricity and inadequate digital infrastructure. These infrastructure gaps are compounded by human capacity constraints, as many farmers, extension workers, and even government officials lack the skills and knowledge needed to effectively leverage digital tools.

The challenge of ensuring equitable access to digital solutions emerges as a critical concern throughout the analysis. Women farmers face barriers to digital adoption due to sociocultural constraints, limited access to mobile devices, lower digital literacy rates and exclusion from formal financial systems. Indigenous Peoples communities and ethnic minorities often find that digital solutions fail to accommodate their languages, cultural practices and traditional knowledge systems. The elderly and youth face different but equally significant challenges in accessing and benefiting from digital agricultural services.

The governance challenges associated with digital transformation in agriculture raise fundamental questions about data ownership, privacy, algorithmic accountability and technological sovereignty. As digital platforms collect vast amounts of data about farming practices, land use and market transactions, concerns grow about how this data is used, who benefits from its value and what rights farmers have over their own information. The concentration of advanced technological capabilities in a handful of global technology companies creates dependencies that may limit local innovation and perpetuate existing power imbalances in global agrifood systems.

The experiences documented throughout the report point to several critical insights for moving forward. First, **technology alone cannot transform disaster risk management in agriculture without corresponding investments in human capacity, institutional development and enabling infrastructure**. The most successful digital interventions are those that combine technological innovation with sustained capacity building, participatory design processes and integration into existing institutional frameworks.

Second, **comprehensive approaches that address multiple dimensions of risk and vulnerability prove more effective** than narrow, technology-focused interventions. Digital early-warning systems achieve greater impact when linked to anticipatory financing mechanisms, community preparedness programmes and social protection systems that can deliver rapid support to affected populations.

Third, the **importance of context-specific solutions** emerges clearly from the implementation experiences. Digital tools that succeed in one context may fail in another due to differences in infrastructure, institutional capacity, cultural factors or risk profiles. This highlights the need for adaptive approaches that can be tailored to local conditions while maintaining interoperability with broader systems.

Finally, **the critical role of partnerships and collaboration** becomes evident throughout the analysis. Successful digital transformation requires bringing together diverse stakeholders, including government agencies, technology providers, research institutions, civil society organizations and farming communities themselves in new forms of collaboration that transcend existing sectoral boundaries.

STRATEGIC PRIORITIES AND PATHWAYS FORWARD

Building on these insights, several priority areas emerge for transformative action.

The **development of integrated assessment frameworks** that capture the full spectrum of disaster impacts in agriculture represents a fundamental requirement for evidence-based risk management. These frameworks must expand beyond economic metrics to systematically assess nutritional impacts, ecosystem service disruptions, cultural heritage losses and differential social effects. They must adopt longitudinal approaches that track impacts over multiple years to capture slow-onset processes and long-term recovery trajectories. The integration of multiple data sources, including remote sensing, household surveys, community assessments and Indigenous knowledge systems, can provide a more comprehensive understanding of disaster impacts that informs more effective responses.

The **standardization of methodologies**, while maintaining flexibility for local contexts, represents a delicate balance that must be achieved. Global comparability requires common indicators and assessment protocols, yet the diversity of agricultural systems, hazard profiles and cultural contexts demands adaptability. The new DELTA Resilience System developed by UNDRR represents a promising step towards achieving this balance, but its success will depend on widespread adoption, adequate resourcing and genuine commitment to comprehensive impact assessment that goes beyond simple economic accounting. Continued support for capacity development is critical to ensure that national and local actors can effectively implement and sustain these systems.

Bridging the digital divide through people-centred innovation emerges as perhaps the most critical challenge for ensuring that digital transformation benefits all agricultural communities. This requires comprehensive strategies that address not only technical infrastructure but also human capacity, affordability and cultural appropriateness. Investment in rural digital infrastructure, including reliable electricity, internet connectivity and mobile network coverage, provides the foundation for digital transformation but must be accompanied by efforts to ensure that services are accessible and relevant to diverse user communities.

The **development of tiered technological solutions** that function across different levels of digital maturity can help ensure that no communities are left behind. While advanced AI-powered analytics may benefit large-scale commercial farmers, smallholder farmers may derive greater value from simple SMS-based advisory services or interactive voice response systems that work on basic mobile phones. The key lies in creating interconnected ecosystems where different technologies can coexist and complement each other rather than pursuing one-size-fits-all solutions.

Strengthening data governance and interoperability represents another critical priority for sustainable digital transformation. The establishment of robust governance frameworks must balance the need to protect farmers' rights and privacy with the imperative to enable innovation and data sharing for collective benefit. National data governance frameworks should clarify ownership, access rights and usage permissions for agricultural data while establishing accountability mechanisms for algorithmic decision-making systems. The development of data cooperatives or trusts that give farmers collective bargaining power over their data represents one promising approach for ensuring equitable benefit-sharing from the value created by agricultural data.

Interoperability standards that enable seamless data exchange between platforms – while ensuring security and privacy – are essential to prevent fragmentation. They also play a key role in maximizing the value of digital investments. These standards must be developed through processes that involve all stakeholders and reflect the needs of diverse agricultural systems. Regional and global agreements on data sharing can facilitate cross-border collaboration for managing transboundary risks while respecting national sovereignty and local ownership of data resources.

The **integration of digital solutions into national strategies and institutional frameworks** represents a crucial step for moving beyond pilot projects to achieve systemic transformation at scale. National digital agriculture strategies that explicitly incorporate disaster risk reduction objectives and align with national adaptation plans can provide coherent frameworks for coordinating investments and avoiding duplication. These strategies must be developed through participatory processes that engage all relevant stakeholders and reflect local priorities and capabilities.

The **mainstreaming of digital solutions into agricultural policies, extension services, and rural development programmes** requires institutional coordination mechanisms that bring together institutionally divided agencies and sectors. Agriculture, disaster risk management, meteorological services, and digital development agencies must work together in new ways that break down silos and enable integrated approaches to risk management. The establishment of regulatory sandboxes that allow controlled experimentation with innovative digital solutions while managing risks can help accelerate innovation while maintaining appropriate safeguards.

Scaling anticipatory action through digital innovation offers a promising pathway for managing risks in agriculture and complementing broader DRR efforts. The evidence consistently demonstrates exceptional returns on investment for anticipatory action, with benefit–cost ratios often exceeding 7:1 in avoided disaster impacts. Expanding early warning coverage to include all major agricultural hazards, with particular attention to slow-onset events and compound risks, requires sustained investment in monitoring infrastructure, analytical capabilities and institutional coordination.

The development of **anticipatory action protocols that link early-warning triggers to**

pre-arranged financing is essential to enable timely agricultural emergency interventions, thereby reducing disaster impacts and supporting broader resilience-building efforts. Trigger mechanisms must be based on robust scientific evidence, incorporate local knowledge and priorities and maintain sufficient flexibility to adapt to evolving risk patterns. Creating layered financing architectures that combine insurance, social protection, contingent credit, and humanitarian funding can provide comprehensive coverage for different types and scales of disasters while avoiding gaps and duplications.

Fostering **innovation ecosystems that support sustained technological development and adaptation** represents a long-term investment in enhancing agricultural resilience. The establishment of innovation hubs and incubators focused on disaster risk reduction in agriculture can bring together entrepreneurs, researchers, farmers, and investors to develop and scale solutions for specific challenges. Challenge funds and prizes that incentivize innovation for particular risk management problems can mobilize creative solutions while building local technological capacity.

Supporting **local technology development through capacity building, mentorship, and access** to advanced technologies helps ensure that innovations reflect local needs and capabilities rather than imposing external solutions. Public–private research partnerships that combine academic rigour with private sector innovation and public sector scale can accelerate the development and deployment of effective solutions. The promotion and protection of open-source solutions that can be adapted and improved by local communities helps democratize access to digital tools while fostering continuous innovation.

Investment in human capital and institutional capacity emerges as perhaps the most critical factor for sustainable digital transformation. Technology alone cannot create change without people who understand how to use, maintain and improve digital systems. Comprehensive digital literacy programmes targeting farmers, extension workers, and government officials must go beyond basic computer skills to develop critical thinking about how digital tools can enhance agricultural practices and risk management. Creating career pathways for digital agriculture specialists who combine technical skills with agricultural knowledge helps build a sustainable workforce for digital transformation.

The **establishment of centres of excellence** for digital disaster risk reduction that provide training, research, and technical support can serve as knowledge hubs that accelerate learning and innovation across regions. Building change management capacity helps institutions adapt to digital transformation by addressing not only technical requirements but also organizational culture, processes and incentive structures. Fostering communities of practice that enable peer learning and continuous improvement creates sustainable mechanisms for knowledge sharing and collective problem-solving.

While digital solutions offer powerful tools for risk management, they must be **complemented by efforts to address underlying systemic vulnerabilities** that perpetuate disaster risk and constrain adaptive capacity. Strengthening social protection systems that can be rapidly scaled during disasters through digital delivery mechanisms provides crucial safety nets for vulnerable populations. Investment in climate-resilient infrastructure, including irrigation systems, storage facilities and transportation networks, reduces exposure to disaster risks while enabling more effective use of digital tools for risk management.

Promoting agricultural diversification and climate-smart practices builds inherent resilience that reduces dependence on external interventions. Addressing land tenure insecurity and resource access inequalities removes fundamental barriers to investment in risk reduction and adoption of improved practices. Strengthening local institutions and collective action mechanisms enables community-level risk management that complements and enhances technological solutions.

The financial requirements for comprehensive digital transformation and resilience-building are substantial but achievable within the context of current disaster losses and development financing. The USD 3.26 trillion in agricultural losses over the past three decades far exceeds the investments needed for building resilient agrifood systems. Moreover, the evidence consistently shows positive returns on investment in disaster risk reduction, with well-designed interventions generating benefits that far exceed their costs. The question is not whether resources are available but how to mobilize and direct them effectively towards transformative and risk-informed solutions that address root causes and structural vulnerabilities rather than short-term impacts.

International cooperation plays a crucial role in mobilizing resources, sharing knowledge and coordinating action for disaster risk reduction in agriculture. Multilateral organizations must continue to provide technical leadership, facilitate knowledge exchange, and support capacity building while ensuring that solutions reflect local ownership and priorities. Bilateral development partners can support digital transformation through targeted investments in infrastructure, capacity building, and innovation, while aligning their efforts with national strategies and avoiding fragmentation.

The private sector brings essential innovation, efficiency, and resources to digital transformation but must be engaged in ways that ensure equitable access and benefit sharing. Public–private partnerships that align commercial incentives with development objectives can mobilize private investment while maintaining focus on reaching vulnerable populations. Clear frameworks for corporate engagement that establish expectations for responsible business conduct, data governance and collaborative design help ensure that private sector participation enhances rather than undermines development objectives.

Civil society organizations play vital roles in advocating for participatory solutions, monitoring implementation and ensuring accountability of all actors. Their deep connections with farming communities and understanding of local contexts make them essential partners in designing and implementing digital solutions that truly serve user needs. Supporting civil society capacity to engage with digital transformation helps ensure that technological change reflects social priorities and values.

As we look towards the future, several emerging trends and technologies hold promise for further transforming disaster risk management in agriculture. The convergence of AI, IoT sensors, blockchain and advanced satellite technologies creates possibilities for integrated risk management systems of unprecedented sophistication. Edge computing that enables real-time data processing at the field level could overcome connectivity constraints while enabling faster response times. Quantum computing may revolutionize our ability to process complex climate models and predict agricultural risks with far greater accuracy than current systems allow.

However, realizing this potential requires proactive efforts to shape technological development in directions that serve agricultural resilience and food security objectives. This includes investing in research and development that addresses specific challenges faced by smallholder farmers and vulnerable communities rather than assuming that technologies developed for other purposes will automatically benefit agriculture. It requires establishing ethical frameworks for AI and automated decision-making that protect human agency and prevent algorithmic bias from perpetuating existing inequalities.

The journey towards digitally enabled agricultural resilience is not merely a technical challenge but a societal transformation that requires vision, leadership and sustained commitment from all stakeholders. Success demands moving beyond fragmented project-based approaches to create systemic change that transforms how we understand, reduce and manage disaster risks, as well as how we prepare for and respond to disasters. This transformation must be grounded in principles of sustainability and human dignity that ensure technological progress serves the common good rather than exacerbating existing inequalities.

The convergence of escalating disaster risks and transformative digital capabilities creates both an urgent imperative and an unprecedented opportunity for action. The window for building resilient agrifood systems capable of feeding a growing global population while adapting to climate shocks is narrowing rapidly. Yet the tools, knowledge, and examples of success documented throughout this report demonstrate that transformation is possible when vision aligns with action and resources match ambition.

The path forward requires collective action that transcends prevailing boundaries between sectors, disciplines and institutions. Governments must provide visionary leadership and enabling environments that foster innovation while protecting vulnerable populations. The private sector must contribute technological innovation and investment while ensuring that solutions remain accessible and beneficial to all. Civil society must continue to advocate for people-centred approaches and hold all actors accountable for their commitments. International organizations must facilitate coordination and knowledge sharing while respecting local ownership and diverse pathways to resilience.

Most fundamentally, farming communities themselves must be recognized and empowered as primary agents of change rather than passive beneficiaries of external interventions. Their knowledge, priorities and innovations must shape the digital transformation of agriculture rather than having solutions imposed upon them. Building truly resilient agrifood systems requires combining the wisdom and collective knowledge accumulated through generations of farming experience with the possibilities opened by digital innovation in ways that respect both tradition and transformation.

As we stand at this critical juncture, the choices made today will determine the resilience and sustainability of global agrifood systems for generations to come. The digital revolution offers powerful tools for transformation, but tools alone do not create change. Change requires visionary policies, institutional commitment and multistakeholder engagement to build agrifood systems that can not only survive but thrive in the face of mounting challenges. The responsibility to act rests with all of us, and the time for transformative action is now. Through sustained commitment to people-centred digital transformation of disaster risk reduction that addresses both technological and systemic challenges, we can build a future where agricultural communities are empowered to design and drive their own resilience solutions, effectively manage and reduce risks, adapt to change and ensure food security for all. ■

TECHNICAL ANNEXES

ANNEX 1
DAMAGE AND LOSS CALCULATIONS FROM POST-DISASTER NEED ASSESSMENTS

PDNAs are available online and were downloaded from PreventionWeb,[213] ReliefWeb,[214] the Global Facility for Disaster Reduction and Recovery (GFDRR)[215] and World Bank[216] websites. The data sources used in this report span the period from 2007 to 2022.

In particular, data were retrieved from 88 post-disaster assessment exercises conducted in 60 countries across seven regions and subregions, as follows: Africa, 30; Asia, 24; Caribbean, 10; Eastern Europe, 8; Near East, 1; Oceania, 10; and South America, 5. The data cover nine hazard types: cyclone, 5; drought, 7; earthquake, 9; flood, 32; industrial accident, 1; multihazard, 6 (including La Niña, 1); landslide and flood, 3; COVID-19 pandemic, 2; storm, 23; tsunami, 1; and volcanic activity, 4. This pool of PDNAs included different assessment types, particularly damage, loss and needs assessments; post-disaster needs assessments; and rapid damage and needs assessments.

PDNAs produce damage and loss estimates by economic sector, which makes it possible to compare impacts across the economy. All reported damage and loss values were converted to USD for 2017 (either from the current USD values or local currency unit) using consumer price index data from the World Bank.[217]

To calculate the total agricultural losses caused by disaster types, damage and loss values reported were summed up and aggregated by hazard category. The industrial accidents reported did not include impact values for the agricultural sector and thus are not displayed as a category in the results.

The share of agricultural losses in productive sector losses corresponds to the reported damage and loss in agriculture for all PDNAs, divided by the total reported damage and loss for all the productive sectors of all PDNAs (including agriculture, industry, commerce and trade, and tourism) by disaster category.

Similarly, the share of agricultural losses in total losses is calculated by dividing the reported damage and loss in agriculture for all PDNAs by the total reported damage and loss for all PDNAs, by disaster category.

A subsector breakdown of the reported damage and loss was provided for 50 PDNAs, which accounts for 56 percent of the sample. For this subsample, damage and loss by the agricultural subsector were aggregated in 2017 USD to compute the respective shares.

ANNEX 2
ESTIMATING GLOBAL CROP AND LIVESTOCK LOSSES FROM DISASTERS

This annex describes the methodology used to estimate the economic value of losses in crop and livestock production due to natural disasters between 1991 and 2023. The analysis is based on a counterfactual scenario approach, wherein estimated production levels assuming no disaster occurrence are compared against reported production data to assess loss magnitude. The methodology covers 205 countries or areas and includes 191 agricultural commodities grouped into nine crop categories and three livestock product categories.

Data source

Four data sources are used to estimate the different parameters of the models.

- *Disaster data*: The occurrence of disasters is taken from the EM-DAT database,[217] which provides the most comprehensive coverage of historical disaster events. The disasters recorded in this database meet the criteria of either ten or more dead, 100 or more injured, a declaration of a state of emergency or a call for international assistance. All scales of disaster events – small, medium and large – falling under the following hazard categories are included in the analysis: storm, flood, drought, extreme temperature, insect infestation, wildfire, earthquake, landslide, mass movement and volcanic activity. The global count for these disasters was 10 227 events from 1991 to 2023.
- *Production and price data*: Crop production, area harvested, yield, and livestock statistics (animal numbers, slaughter data) were sourced from FAOSTAT,[218] disaggregated by commodity and country. Prices are reported in 2017 international dollars (PPP-adjusted).
- Agricultural total factor productivity data from 1991–2023 were retrieved from the United States Department of Agriculture.[219]

The present methodology adopts a counterfactual estimation perspective. The implemented counterfactual model depends on the availability of years without disasters; when five or more years are available, a Kalman state-space model is used. On the other hand, when there is not enough data to effectively capture the temporal structure of observations, a combination of clustering, regression methods and dynamic time warping is implemented. This process, embedded in an adaptive jackknife scheme, provides an estimate of the distribution of losses.

Kalman state-space model

Given y_t, a time series of observable elements, these are related to an $m \times 1$ vector α_t, known as the state vector, through the following measurement equation:

$$y_t = z_t'\alpha_t + d_t + \varepsilon_t\,, \quad \forall t = 1,2,\dots,T$$

$$\varepsilon_t \sim i.i.d\ N(0, V_\varepsilon)$$

Where z_t and d_t are $m \times 1$ and a $T \times 1$ constant vectors, respectively. Generally, α_t are not observable, however, they are supposed to follow a first-order autoregressive model:

$$\alpha_{t+1} = T_t\alpha_t + c_t + R_t\eta_t, \quad \eta_t \sim i.i.d\ N(0, W_\eta)$$

Here, T_t is $m \times m$ matrix, c_t is a $m \times 1$ vector and R_t is a $m \times g$ matrix. The model specification is completed with the following hypothesis.

$$\begin{cases} E(\alpha_0) = a_0\ y\ V(\alpha_0) = P_0 \\ \quad E(\varepsilon_t\eta_t') = 0 \end{cases}$$

In this context, α_t will represent the real yield levels of an item in a certain country. On the other hand, y_t represents the reported yield in FAOSTAT. It is coherent to consider it as an observable proxy for the actual yield, as these values are typically reported by national statistics offices using survey sampling methods and are subject to both sampling and non-sampling errors.

Compound model

Given the multivariate time series $Y_t = [Y'_{t1}, Y'_{t2}, Y'_{ti}, \dots, Y'_{tN}]$ for observed yields of item i, where each row contains information from a specific country, the objective is to build a regression model that enhances the quality of the estimation by leveraging data from other countries. For this reason, countries are first divided into groups based on a hierarchical clustering approach implemented by using $X = [x'_1, x'_2, \dots, x'_i, x'_N]$ and TFP as auxiliary variables, where:

$$x_{ij} = \sum_{k=2015}^{2023} \frac{y_{tij}}{9}$$

TFP contains the output of a hierarchical clustering approach on total factor productivity for the years 1994 to 2023, using a dynamic time warping dissimilarity measure.[220] Once both X and TFP are available, a Factor Analysis of Mixed Data (FAMD)[221] is applied to reduce the dimensionality of the combined dataset. Finally, a hierarchical clustering approach is implemented, resulting in a set of country clusters. To obtain the estimates, the following components are computed:

$$MYL_{tij} = \sum_{k \in Cluster_j} \frac{y_{tik}}{\#Cluster_j}$$

Mean yield level of item i, in cluster j in year t.

$$MGR_{tij} = \frac{MYL_{tij}}{MYL_{(t-1)ij}}$$

Mean growth rate of item i, in cluster j in year t.

Finally, given a country and an item, counterfactual estimates for year t are computed as:

$$\hat{y}_t = y_{t-1} \times MGR_{t,i,CC}$$

where CC is the country's cluster.

Estimation and null hypothesis

To simulate uncertainty and establish a robust estimate, the algorithm repeatedly samples a subset of non-disaster years and temporarily removes their yield values. These missing values are then interpolated using either a Kalman state–space model or a compound model, depending on the amount of available information. This process generates a counterfactual yield series that reflects what yields might have been in the absence of disasters.

Yield losses are calculated as the difference between actual and counterfactual yields during disaster years, as well as during the simulated non-disaster years. By repeating this procedure multiple times, the algorithm builds a distribution of yield losses under disaster conditions.

In parallel, the same method applied to non-disaster years allows the construction of a **null distribution**. This is the distribution of yield variations in the absence of disasters. This null distribution is used to assess the statistical significance and typical variability of estimated losses.

Distribution of losses by disaster type

To ensure an accurate attribution of economic losses and prevent overestimation, a correction was applied in cases where multiple disasters were recorded affecting the same country, crop, and year. Total estimated loss for that unit was proportionally distributed among the disasters reported. This weighting approach ensures that losses are not double-counted when multiple disasters coincide temporally. Only disasters for which yield losses were found to be statistically significant, based on the **null distribution**, were considered. Losses were then aggregated using these weights, the final outputs allow for disaggregated and comparable loss assessments while maintaining methodological rigour across regions, crops, and disaster types.

ANNEX 3
NUTRIENT LOSSES IN THE FOOD SUPPLY

From the global disaster losses estimated in agricultural production over 1991–2023, nutritional losses are computed for energy and nine micronutrients, representing their reduced availability in the global food supply. Crop and livestock commodities lost due to disasters are matched to appropriate foods and their related nutrient values in the global nutrient conversion table for calcium, iron, zinc, vitamin A, thiamin, riboflavin, vitamin C, magnesium and phosphorus, considering their edible coefficient.[222] Total losses of nutrients from 1991 to 2023 are divided by the world population and days in this period to convert values into the average quantity of energy and nutrients lost per person per day due to disasters. The national population data used was retrieved from FAOSTAT.[219] To express values as a percentage of human requirements for these nutrients, the daily per capita loss of each nutrient is divided by its estimated average EAR for adult men and women.

GLOSSARY

Algorithm: A set of steps followed to solve a mathematical problem or complete a computer process.[223]

Agricultural assets: The volume of stored inputs and production (seeds, fertilizer, feed, stored crops and livestock produce, harvested fish, stored wood, etc.) and machinery and equipment used in crop and livestock farming, forestry and fisheries and aquaculture. It encompasses a wide array of items, including but not limited to: tractors, balers, combine harvesters, threshers, fertilizer distributors, ploughs, root or tuber harvesting machines, seeders, soil machinery, irrigation facilities, tillage implements, track-laying tractors, milking machines, dairy machines, specialized wheeled equipment, portable chainsaws, fishing vessels, fishing gear, aquaculture feeders, pumps, aerators and support vessels for aquaculture.

Agricultural production loss: A decline in the volume of crop and livestock production, as well as forestry, and fisheries and aquaculture production, resulting from a disaster compared with pre-disaster expectations.

Agrifood systems: Systems that encompass the primary production of food and non-food agricultural products, as well as in food storage, aggregation, post-harvest handling, transportation, processing, distribution, marketing, disposal and consumption. Within agrifood systems, food systems comprise all food products that originate from crop and livestock production, forestry, fisheries and aquaculture, and from other sources, such as synthetic biology that are intended for human consumption.[224]

Artificial intelligence: The simulation of human intelligence in machines that are programmed to think like humans and mimic their actions. The term may also be applied to any machine that exhibits traits associated with a human mind, such as learning and problem-solving. The ideal characteristic of AI is its ability to rationalize and take actions that have the best chance of achieving a specific goal. A subset of AI is machine learning, which refers to the concept that computer programmes can automatically learn from and adapt to new data without being assisted by humans. Deep learning techniques enable this automatic learning through the absorption of huge amounts of unstructured data such as text, images or video.[223]

Biological hazards: Hazards of organic origin or conveyed by biological vectors, including pathogenic microorganisms, toxins and bioactive substances. Examples include bacteria, viruses or parasites, as well as venomous wildlife and insects, poisonous plants and mosquitoes carrying disease-causing agents.

Blockchain: A technology that provides decentralization, immutability and transparency for data, and where the data are organized in a growing list (chain) of data structures (called blocks). Examples of blockchains are Bitcoin and Ethereum, the latter of which added the notion of smart contracts.[223]

Climate: Climate is usually defined as the average weather, but it is more rigorously defined as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years.[225]

Climate change: Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties that persist for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.[225] In its Article 1, the UNFCCC defines it as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."[226]

Climate change adaptation: In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to the expected climate and its effects.[225]

Climate resilience: The capacity of social, economic and environmental systems to cope with current or expected climate variability and changing average climate conditions, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.[225]

Climate variability: Variations in the mean state and other statistics (standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Climatological disasters: A disaster caused by long-lived, meso- to macro-scale atmospheric processes ranging from intraseasonal to multidecadal climate variability.[227]

Cloud computing: Cloud computing is the delivery of different services through the internet. These resources include tools and applications like data storage, servers, databases, networking and software. Rather than keeping files on a proprietary hard drive or local storage device, cloud-based storage makes it possible to save them to a remote database. As long as an electronic device has access to the World Wide Web, it has access to the data and the software to run it.[223]

Coping capacity/capacity to cope: The ability of people, organizations and systems, using available skills and resources, to manage adverse conditions, risk or disasters. The capacity to cope requires continuing awareness, resources and good management, both in normal times as well as during disasters or adverse conditions. Coping capacities contribute to the reduction of disaster risks.[226]

Damage: The monetary value of the total or partial destruction of physical assets and infrastructure in disaster-affected areas, expressed as replacement and/or repair costs. In agriculture, damage is considered in relation to standing crops, farm machinery, irrigation systems, livestock shelters, fishing vessels, pens and ponds, etc.[226]

Digital agriculture: Often referred to as digital agriculture, this is a process involving digital technologies (such as the Internet of Things, artificial intelligence, blockchain, etc.) that encompasses access, content and capabilities. When appropriately combined for the local context and needs within existing food and agricultural practices, it can deliver high agrifood value and contribute to improving socioeconomic and potentially environmental outcomes.[223]

Digital farming: The essence of digital farming lies in creating value from data. Digital farming intends to go beyond the presence and availability of data to develop actionable intelligence and meaningful added value from such data. Digital agriculture integrates both precision farming and smart farming.[223]

Digital solution: In the context of agrifood systems, a digital solution refers to any digital technology, service, or innovation with a clearly defined ICT, combined with specific target functions related to one or more aspects of the agrifood systems. These solutions encompass a wide range of applications, from farm management and market access to early warning systems and data analysis, all aimed at improving food security, livelihoods and environmental sustainability. Digital solutions must be beyond the proof-of-concept stage and need to demonstrate evidence of use and deployment and, if available, impacts.[228]

Digital technology: Digital technology is an all-encompassing term to refer to computerized tools that generate, store and use data for a variety of purposes.[229]

Disaster: A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental loss and impacts.[226]

Disaster risk: The potential loss of life, injury, or destroyed or damaged assets, which could occur to a system, society or a community in a specific period, determined probabilistically as a function of hazard, exposure, vulnerability and capacity. The definition of disaster risk reflects the concept of hazardous events and disasters as the outcome of continuously present conditions of risk.[226]

Disaster risk management: Disaster risk management is the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses.[230]

Disaster risk reduction: The policy objective of disaster risk management. DRR strategies and plans are designed with the objective of preventing the emergence of new disaster risks, reducing existing risks and effectively managing remaining risks. These efforts collectively enhance resilience and align with the overarching aim of promoting sustainable development.[226]

Displacement: Situations where people are forced or obliged to leave their homes or places of habitual residence due to a disaster or to avoid the impact of an immediate and foreseeable natural hazard. This displacement occurs because individuals who are exposed to a natural hazard are in a situation where they are exceptionally vulnerable and lack the necessary resilience to withstand the impacts of that hazard. It is the effects of natural hazards, including the adverse impacts of climate change, that may overwhelm the resilience or adaptive capacity of an affected community or society, thus leading to a disaster that potentially results in displacement. Disaster displacement may take the form of spontaneous flight, an evacuation ordered or enforced by authorities, or an involuntary planned relocation process. This displacement can take place within a single country, referred to as internal displacement, or it can extend across international borders, known as cross-border disaster displacement.[231]

Early-warning system: An integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities, systems and processes that enable individuals, communities, governments, businesses and others to take timely action to reduce the effects of disaster in advance of hazardous events.[226]

Extreme event (extreme weather event or extreme climate event): An event that is rare at a particular place and time of year. Definitions of rare vary, but the occurrence of an extreme weather event would be at a value of a weather or climate of weather variable above or below a threshold value near the upper or lower ends of the range of observed values of the variable. By definition, the characteristics of extreme weather may vary from place to place. When a pattern of extreme weather persists for a season or longer, it may be classified as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g. drought or heavy rainfall over a season).[225]

Food insecurity: A situation that exists when people lack secure access to enough safe and nutritious food for normal growth and development and an active and healthy life. It may be caused by the unavailability of food, insufficient purchasing power, and inappropriate distribution or inadequate use of food at the household level. Food insecurity, poor conditions of health and sanitation, and inappropriate care and feeding practices are the major causes of poor nutritional status. Food insecurity may be chronic, seasonal or transitory.[232]

Food security: A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Based on this definition, four food security dimensions can be identified: food availability, economic and physical access to food, food utilization and stability over time.[231]

Geophysical disasters: Disasters that originate from the Earth's internal processes, such as earthquakes, volcanic activity and emissions, and related geophysical processes such as mass movements, landslides, rockslides, surface collapses, and debris or mud flows. Hydrological and meteorological factors are important to some of these processes. Tsunamis are difficult to categorize because they are triggered by undersea earthquakes and other geological events, but they essentially become an oceanic process that is manifested as a coastal water-related hazard.[226]

Hazard: A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards may be natural, anthropogenic or socionatural in origin. Natural hazards are predominantly associated with natural processes and phenomena.[226]

Hunger: An uncomfortable or painful physical sensation caused by insufficient consumption of dietary energy.[231]

Hydrological disasters: Disasters caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater.[226]

Internet of Things: The IoT is a computing concept that describes the idea of everyday physical objects being connected to the internet and being able to identify themselves to other devices and to send and receive data. The IoT is significant because an object that can represent itself digitally becomes something greater than the object alone. No longer does the object relate just to its user, but it is connected to surrounding objects and database data.[223]

Loss: The change in economic flows occurring due to a disaster. In agriculture, loss may include declines in crop production, decline in income from livestock products, increased input prices, reduced overall agricultural revenues and higher operational costs, and increased unexpected expenditures to meet immediate needs in the aftermath of a disaster.[226]

Machine learning: The concept that a computer programme can learn and adapt to new, unstructured and unlabelled data without human intervention. ML is a subset of artificial intelligence.[223]

Marine heatwave: A period during which water temperature is abnormally warm for the time of the year relative to historical temperatures, with that extreme warmth persisting for days to months. The phenomenon can manifest in any place in the ocean and at scales of up to thousands of kilometres.[233]

Micronutrients: Micronutrients include vitamins and minerals and are required in very small (micro) but specific amounts. Vitamins and minerals in foods are necessary for the body to grow, develop and function properly, and are essential for our health and well-being. Our bodies require a number of different vitamins and minerals, each of which has a specific function in the body and must be supplied in different, sufficient amounts.[231]

Migration: The movement of a person or a group of people, either across an international border or within a state. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes. It includes migration of refugees, displaced persons, economic migrants and persons moving for other purposes, including family reunification.

Mitigation (of disaster risk and disaster): The efforts aimed at reducing the potential adverse impacts of a hazardous event, including those caused by human activities. This reduction is achieved through actions that target the reduction of hazard, exposure and vulnerability.[226]

Multihazard early-warning systems: Systems that address several hazards and/or impacts of similar or different types in contexts where hazardous events may occur alone, simultaneously, in a cascading manner or cumulatively over time, taking into account potential interrelated effects. A multihazard early-warning system with the capacity to warn of one or more hazards increases the efficiency and consistency of warnings through coordinated and compatible mechanisms and capacities, involving multiple disciplines for updated and accurate hazard identification and monitoring.[229]

Preparedness: The knowledge and capacities developed by governments, response and recovery organizations, communities and individuals to effectively anticipate, respond to and recover from the impacts of a likely, imminent or current disaster.[226]

Prevention: Activities and measures to avoid existing and new disaster risks. Disaster prevention expresses the concept and intention to completely avoid potential adverse impacts of hazardous events.[226]

Recovery: Restoring or improving the livelihoods and health, and the economic, physical, social, cultural and environmental assets, systems and activities of a disaster-affected community or society, in line with the principles of sustainable development and "build back better" to avoid or reduce future disaster risk.[226]

Rehabilitation: The restoration of basic services and facilities for the functioning of a community or a society affected by a disaster.[226]

Resilience: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.[226]

Residual risk: The disaster risk that remains even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained. The presence of residual risk implies a continuing need to develop and support effective capacities for emergency services, preparedness, response and recovery, together with socioeconomic policies such as safety nets and risk transfer mechanisms, as part of a holistic approach.[226]

Slow-onset disaster: A disaster that emerges gradually over time. Slow-onset disasters could be associated with drought, desertification, sea-level rise, epidemic diseases, etc.[226]

Societal hazard: Hazards brought about entirely or predominantly by human activities and choices, that have the potential to endanger exposed populations and environments. They are derived from sociopolitical, economic and cultural activities, human mobility and the use of technology, as well as from societal behaviour – whether intentional or unintentional.[232]

Sudden-onset disaster: A disaster triggered by a hazardous event that emerges quickly or unexpectedly. Sudden-onset disasters could be associated with earthquakes, volcanic eruptions, flash floods, chemical explosions, critical infrastructure failures, transport accidents, etc.[226]

Vulnerability: The conditions determined by physical, social, economic and environmental factors or processes that increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.[226]

NOTES

1 **UNOCHA.** 2023. Horn of Africa: Humanitarian update – With the emergency far from over, immediate action is required to save lives and prevent the next catastrophe. In: *United Nations Office for the Coordination of Humanitarian Affairs*. New York. [Cited 12 June 2025]. https://www.unocha.org/publications/report/ethiopia/horn-africa-humanitarian-update-emergency-far-over-immediate-action-required-save-lives-and-prevent-next-catastrophe-may-2023

2 **Cabezas, G.** 2025. The impact of climate change and irregular weather patterns on agriculture in South America in 2024. In: *Tridge Opinion*. [Cited 12 June 2025]. https://www.tridge.com/stories/the-impact-of-climate-change-and-irregular-weather-patterns-on-agriculture-in-south.

3 **UNOCHA.** 2023. Pakistan: 2022 monsoon floods – Situation Report No. 19 (as of 12 August 2023). In: *ReliefWeb*. [Cited 12 June 2025]. https://reliefweb.int/report/pakistan/pakistan-2022-monsoon-floods-situation-report-no-19-12-august-2023

4 **ACAPS.** 2023. Libya: Impact of Storm Daniel in eastern Libya and the collapse of dams in Derna – Briefing note, 13 September 2023. In: *ReliefWeb*. [Cited 12 June 2025]. https://reliefweb.int/report/libya/libya-impact-storm-daniel-eastern-libya-and-collapse-dams-derna-briefing-note-13-september-2023

5 **UNOCHA.** 2024. The humanitarian impacts of El Niño in Southern Africa – September 2024. In: *United Nations Office for the Coordination of Humanitarian Affairs*. [Cited 14 June 2025]. https://www.unocha.org/publications/report/mozambique/humanitarian-impacts-el-nino-southern-africa-september-2024

6 **Oxfam.** 2023. 100 days since Cyclone Freddy, farmers in Malawi and Mozambique have nothing to grow ahead of the winter. News release, 21 June 2023. In: *ReliefWeb*. [Cited 12 June 2025]. https://reliefweb.int/report/malawi/100-days-cyclone-freddy-farmers-malawi-and-mozambique-have-nothing-grow-ahead-winter

7 **DEFRA.** 2024. African swine fever (ASF) in Asia. Updated outbreak assessment No. 26. In: *Department for Environment, Food and Rural Affairs, UK Government*. [Cited 20 June 2025]. https://assets.publishing.service.gov.uk/media/66c85e381f215d9f0a913535/asf_asia_update_26.pdf

8 **FAO.** 2025. Desert Locust Bulletin No. 559 – April 2025. In: *FAO Desert Locust Information Service*. [Cited 2 June 2025]. https://openknowledge.fao.org/server/api/core/bitstreams/02db80fc-aa40-4460-83b2-33134eb2b134/content

9 **CIFFC.** 2025. National fire situation report. 9 July 2025. In: *Canadian Interagency Forest Fire Centre Inc.* [Cited 11 July 2025]. https://ciffc.net/situation/2025-07-09

10 Xinhua. (2025, August 15). Heat, drought, negligence: drivers of Europe's 2025 wildfire crisis. Xinhua / English.News.cn. Retrieved from https://english.news.cn/20250815/a14d90aaea9b4d0a94a4c5c0c1b40347/c.html

11 **Mercator Ocean International.** 2024. Marine heatwave forecasts: August 15th 2024, warmest surface temperature in the Mediterranean Sea. In: *Mercator Ocean International*. [Cited 16 June 2025]. https://www.mercator-ocean.eu/wp-content/uploads/2024/08/Temperature_record_August2024_MedSea.pdf

12 **FAO.** 2024. *El Niño impacts and policies for the fisheries sector.* FAO Innovation for Blue Transformation. Rome. https://doi.org/10.4060/cd3812en

13 **GRFC.** 2025. Regional and country overviews: Africa, West and the Sahel – Conflict and insecurity in the region. In: *Global Report on Food Crises*. [Cited 7 July 2025]. https://www.fsinplatform.org/sites/default/files/resources/files/GRFC2025-focus-conflict-WA.pdf

14 **European Commission. Joint Research Centre.** 2020. *Global warming and drought impacts in the EU: JRC PESETA IV project : Task 7*. Publications Office. https://data.europa.eu/doi/10.2760/597045

15 **European Commission. Joint Research Centre.** 2020. *Global warming and drought impacts in the EU: JRC PESETA IV project : Task 7*. LU, Publications Office. https://data.europa.eu/doi/10.2760/597045

16 **White, R.H., Anderson, S., Booth, J.F., Braich, G., Draeger, C., Fei, C., Harley, C.D.G. *et al.*** 2023. The unprecedented Pacific Northwest heatwave of June 2021. *Nature Communications*, 14(1): 727. https://doi.org/10.1038/s41467-023-36289-3

17 **Centre for Research on the Epidemiology of Disasters (CRED).** n.d. *The International Disaster Database (EM-DAT)*. [Accessed on 25 July 2025]. https://public.emdat.be/. Licence: CC-BY-4.0.

18 **Kassegn, A. & Endris, E.** 2021. Review on socio-economic impacts of 'Triple Threats' of COVID-19, desert locusts, and floods in East Africa: Evidence from Ethiopia. *Cogent Social Sciences*, 7(1): 1885122. https://doi.org/10.1080/23311886.2021.1885122

19 **FSIN and Global Network Against Food Crises.** 2021. *Regional focus on the Intergovernmental Authority on Development (IGAD) Member States – Global Report on Food Crises 2021*. Rome. https://www.fsinplatform.org/sites/default/files/resources/files/GRFC%202021%20050521%20med.pdf

20 **UNOCHA.** 2019. Southern Africa: Humanitarian key messages, September 2019. News and press release. In: *ReliefWeb*. [Cited 15 September 2025]. https://reliefweb.int/report/zimbabwe/southern-africa-humanitarian-key-messages-september-2019

21 **Gullino, M.L., Albajes, R., Al-Jboory, I., Angelotti, F., Chakraborty, S., Garrett, K.A., Hurley, B.P. *et al.*** 2022. Climate Change and Pathways Used by Pests as Challenges to Plant Health in Agriculture and Forestry. *Sustainability*, 14(19): 12421. https://doi.org/10.3390/su141912421

22 **Garrett, K.A., Nita, M., De Wolf, E.D., Esker, P.D., Gomez-Montano, L. & Sparks, A.H.** 2021. Plant pathogens as indicators of climate change. In: *Climate Change*. pp. 499–513. Elsevier. https://doi.org/10.1016/B978-0-12-821575-3.00024-4

23 **Biswal, J., Vijayalakshmy, K. & Rahman, H.** 2021. Seasonal Variations and Its Impacts on Livestock Production Systems with a Special Reference to Dairy Animals: An Appraisal. *Veterinary Science Research*, 2(2). https://doi.org/10.30564/vsr.v2i2.2624

24 **Bhattacharjee, P., Warang, O., Das, S. & Das, S.** 2022. Impact of Climate Change on Fruit Crops- A Review. *Current World Environment*, 17(2): 319–330. https://doi.org/10.12944/CWE.17.2.4

25 **Leisner, C.P.** 2020. Review: Climate change impacts on food security- focus on perennial cropping systems and nutritional value. *Plant Science*, 293: 110412. https://doi.org/10.1016/j.plantsci.2020.110412

26 **FAO.** 2018. *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals*. Rome. https://openknowledge.fao.org/handle/20.500.14283/i9540en

27 **Ben Hassen, T., El Bilali, H., Daher, B. & Burkart, S.** 2025. Editorial: Sustainable and resilient food systems in times of crises. *Frontiers in Nutrition*, 12: 1564950. https://doi.org/10.3389/fnut.2025.1564950

28 **Ransom, E.** 2025. Disaster response and sustainable transitions in agrifood systems. *Agriculture and Human Values*, 42(1): 121–138. https://doi.org/10.1007/s10460-024-10625-9

29 **Webb, P., West, K.P. & O'Hara, C.** 2015. Stunting in earthquake-affected districts in Nepal. *The Lancet*, 386(9992): 430–431. https://doi.org/10.1016/S0140-6736(15)61444-1

30 **Vrat, P., Gupta, R., Bhatnagar, A., Pathak, D.K. & Fulzele, V.** 2018. Literature review analytics (LRA) on sustainable cold-chain for perishable food products: research trends and future directions. *Opsearch*, 55: 601–627. https://doi.org/10.1016/j.spc.2021.11.019

31 **Parfitt, J., Croker, T. & Brockhaus, A.** 2021. Global Food Loss and Waste in Primary Production: A Reassessment of Its Scale and Significance. *Sustainability*, 13(21): 12087. https://doi.org/10.3390/su132112087

32 **Cutter, S.L.** 2017. The Perilous Nature of Food Supplies: Natural Hazards, Social Vulnerability, and Disaster Resilience. *Environment: Science and Policy for Sustainable Development*, 59(1): 4–15. https://doi.org/10.1080/00139157.2017.1252603

33 **Kuntke, F., Linsner, S., Steinbrink, E., Franken, J. & Reuter, C.** 2022. Resilience in Agriculture: Communication and Energy Infrastructure Dependencies of German Farmers. *International Journal of Disaster Risk Science*, 13(2): 214–229. https://doi.org/10.1007/s13753-022-00404-7

34 **Elsadek Mahmoudi, S.** 2020. The Propagation of Local Credit Shocks: Evidence from Hurricane Katrina. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3751526

35 **Freeman, J. & Hancock, L.** 2017. Energy and communication infrastructure for disaster resilience in rural and regional Australia. *Regional Studies*, 51(6): 933–944. https://doi.org/10.1080/00343404.2016.1146403

36 **Abedifar, P., Kashizadeh, S. J., & Ongena, S.** 2024. Flood, farms and credit: The role of branch banking in the era of climate change. Journal of Corporate Finance, 85, Article 102544. doi:10.1016/j.jcorpfin.2024.102544.

37 **Weingärtner, L., Simonet, C. & Caravani, A.** 2017. *Disaster risk insurance and the triple dividend of resilience*. London, UK, Overseas Development Institute. https://odi.org/en/publications/disaster-risk-insurance-and-the-triple-dividend-of-resilience/

38 **Elsadek Mahmoudi, S.** 2020. The Propagation of Local Credit Shocks: Evidence from Hurricane Katrina. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3751526

39 **FAO.** 2021. *The impact of disasters and crises on agriculture and food security: 2021*. FAO. https://doi.org/10.4060/cb3673en

40 **Sheu, J.-B. & Kuo, H.-T.** 2020. Dual speculative hoarding: A wholesaler-retailer channel behavioral phenomenon behind potential natural hazard threats. *International Journal of Disaster Risk Reduction*, 44: 101430. https://doi.org/10.1016/j.ijdrr.2019.101430

41 **Malik, A., Li, M., Lenzen, M., Fry, J., Liyanapathirana, N., Beyer, K., Boylan, S. *et al.*** 2022. Impacts of climate change and extreme weather on food supply chains cascade across sectors and regions in Australia. *Nature Food*, 3(8): 631–643. https://doi.org/10.1038/s43016-022-00570-3

42 **Frezal, C., Gay, S.H. & Nenert, C.** 2021. *The Impact of the African Swine Fever outbreak in China on global agricultural markets*. OECD Food, Agriculture and Fisheries Papers. OECD Food, Agriculture and Fisheries Papers 156. https://doi.org/10.1787/96d0410d-en

43 **Khakifirouz, Z., Niknami, M., Keshavarz, M. & Sabouri, M.S.** 2024. From the farmers' point of view, how threatening and harmful are natural hazards? A Q methodology. *International Journal of Disaster Risk Reduction*, 102: 104278. https://doi.org/10.1016/j.ijdrr.2024.104278

44 **Lu, H., Zheng, J., Ou, H., Liu, Y. & Li, X.** 2022. Impact of Natural Disaster Shocks on Farm Household Poverty Vulnerability—A Threshold Effect Based on Livelihood Resilience. *Frontiers in Ecology and Evolution*, 10: 860745. https://doi.org/10.3389/fevo.2022.860745

45 **FAO**. 2024. *The unjust climate – Measuring the impacts of climate change on rural poor, women and youth*. Rome. https://doi.org/10.4060/cc9680en

46 **Saini, S. & Parida, Y.** 2025. Do natural disasters translate into trade disasters? *International Economics*, 182: 100581. https://doi.org/10.1016/j.inteco.2025.100581

47 **Bourova, E., Ramsay, I. & Ali, P.** 2022. The arduous work of making claims in the wake of disaster: Perspectives from policyholders. *Geographical Research*, 60(4): 534–548. https://doi.org/10.1111/1745-5871.12553

48 **Deryugina, T.** 2022. The fiscal consequences of natural disasters. In: W. Kruse, S. Hallegatte & D. Rosenberg, eds. *Handbook on the economics of disasters*. Cheltenham, UK, Edward Elgar Publishing. https://doi.org/10.4337/9781839103735.00019

49 **Ndlovu, E., Prinsloo, B. & Le Roux, T.** 2020. Impact of climate change and variability on traditional farming systems: Farmers' perceptions from south-west, semi-arid Zimbabwe. *Jàmbá: Journal of Disaster Risk Studies*, 12(1). https://doi.org/10.4102/jamba.v12i1.742

50 **Cutter, S.L., Ash, K.D. & Emrich, C.T.** 2016. Urban–Rural Differences in Disaster Resilience. *Annals of the American Association of Geographers*, 106(6): 1236–1252. https://doi.org/10.1080/24694452.2016.1194740

51 **Ingram, L.A., Tinago, C.B., Cai, B., Sanders, L.W., Bevington, T., Wilson, S., Magruder, K.M. & Svendsen, E.** 2018. Examining Long-Term Mental Health in a Rural Community Post-Disaster: A Mixed Methods Approach. *Journal of Health Care for the Poor and Underserved*, 29(1): 284–302. https://doi.org/10.1353/hpu.2018.0020

52 **Nicholson, C.C. & Egan, P.A.** 2020. Natural hazard threats to pollinators and pollination. *Global Change Biology*, 26(2): 380–391. https://doi.org/10.1111/gcb.14840

53 **Girot, P.O.** 2012. Plant disease, pests and erosion of biodiversity. In: B. Wisner, J.C. Gaillard & I. Kelman, eds. *Handbook of hazards and disaster risk reduction*, pp. 384–395. Abingdon, UK, Routledge. https://www.kerwa.ucr.ac.cr/items/b3ab3352-8914-4ac1-b681-0ee80bb99a80

54 **Saco, P.M., McDonough, K.R., Rodriguez, J.F., Rivera-Zayas, J. & Sandi, S.G.** 2021. The role of soils in the regulation of hazards and extreme events. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 376(1834): 20200178. https://doi.org/10.1098/rstb.2020.0178

55 **Ashraf, M., Niaz, Y., Hafeez, M., Ahmad, M.U.D. & Shah, A.A.** 2023. Water Management Strategies for Agricultural Disasters. In: M. Ahmed & S. Ahmad, eds. *Disaster Risk Reduction in Agriculture*. pp. 67–89. Disaster Resilience and Green Growth. Singapore, Springer Nature Singapore. https://doi.org/10.1007/978-981-99-1763-1_4

56 **Malhi, G.S., Kaur, M. & Kaushik, P.** 2021. Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review. *Sustainability*, 13(3): 1318. https://doi.org/10.3390/su13031318

57 **FAO.** 2023. *The impact of disasters on agriculture and food security 2023 – Avoiding and reducing losses through investment in resilience*. Rome. https://doi.org/10.4060/cc7900en

58 **IPCC.** 2019. *Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. In: Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. & Malley, J., eds. [Cited 15 September 2025]. https://www.ipcc.ch/srccl/

59 **Cutter, S.L.** 2017. The forgotten casualties redux: Women, children, and disaster risk. *Global Environmental Change*, 42: 117–121. https://doi.org/10.1016/j.gloenvcha.2016.12.010

60 **J.R., Parida, Y. & Agarwal, P.** 2022. How flood affects rural employment in India: A gender analysis. *International Journal of Disaster Risk Reduction*, 73: 102881. https://doi.org/10.1016/j.ijdrr.2022.102881

61 **FAO.** 2024. *The unjust climate – Measuring the impacts of climate change on the rural poor, women and youth*. Rome. https://doi.org/10.4060/cc9680en

62 **Kreutzer, W., Millerd, C. & Timbs, N.** 2023. Disasters and the diminishing of women's economic empowerment. *Disasters*, 47(4): 891–912. https://doi.org/10.1111/disa.12582

63 **van 't Wout, T., Augustyn, A.M. & Terzic, D.** 2020. Building capacities for agricultural disaster risk reduction in the Western Balkan countries: The case of female farmers in Serbia. In: A. Behnassi, S. Shabbir & M. Nunes Correia, eds. *Food security and land use change under conditions of climatic variability: A multidimensional perspective*, pp. 125–146. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-030-36762-6_7

64 **UNDP.** 2016. Gender, climate change and food security. *Gender and climate change*. In: *United Nations Development Programme*. [Cited 15 September 2025]. https://www.undp.org/publications/gender-climate-change-and-food-security

65 **FAO.** 2024. *The unjust climate – Measuring the impacts of climate change on the rural poor, women and youth*. Rome. https://doi.org/10.4060/cc9680en

66 **Munang, R., Thiaw, I., Alverson, K., Liu, J. & Han, Z.** 2013. The role of ecosystem services in climate change adaptation and disaster risk reduction. *Current Opinion in Environmental Sustainability*, 5(1): 47–52. https://doi.org/10.1016/j.cosust.2013.02.002

67 **Begna, T. & Begna, T.** 2021. Role and economic importance of crop genetic diversity in food security. *International Journal of Agricultural Science and Food Technology*, 7(1): 164–169. https://doi.org/10.17352/2455-815X.000104

68 **Ferguson, M.E., Jones, R.B., Bramel, P.J., Domínguez, C., Torre do Vale, C. & Han, J.** 2012. Post-flooding disaster crop diversity recovery: A case study of cowpea in Mozambique. *Disasters*, 36(1): 83-100. https://doi.org/10.1111/j.1467-7717.2011.01242.x

69 **Sheu, J.-B. & Kuo, H.-T.** 2020. Dual speculative hoarding: A wholesaler-retailer channel behavioral phenomenon behind potential natural hazard threats. *International Journal of Disaster Risk Reduction*, 44: 101430. https://doi.org/10.1016/j.ijdrr.2019.101430

70 **Small, N., Munday, M. & Durance, I.** 2017. The challenge of valuing ecosystem services that have no material benefits. *Global Environmental Change*, 44: 57–67. https://doi.org/10.1016/j.gloenvcha.2017.03.005

71 **UNDRR.** 2016. *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. In: *United Nations Office for Disaster Risk Reduction*. [Cited 15 September 2025]. www.preventionweb.net/publication/report-open-ended-intergovernmental-expert-working-group-indicators-and-terminology

72 **Conforti, P., Markova, G. & Tochkov, D.** 2020. *FAO's Methodology for Damage and Loss Assessment in Agriculture*. FAO Statistics Division Working Paper Series/19-17. Rome, FAO. http://www.fao.org/3/ca6990en/CA6990EN.pdf.

73 **UNDRR.** n.d. Disaster Losses and Damage Tracking System (DELTA Resilience). In: *United Nations Office for Disaster Risk Reduction*. [Cited 25 July 2025]. https://www.undrr.org/building-risk-knowledge/disaster-losses-and-damages-tracking-system-delta-resilience

74 **GFDRR.** 2018. Post-Disaster Needs Assessment (PDNA): Lessons from a decade of experience. In: *Global Facility for Disaster Reduction and Recovery*. [Cited 15 September 2025]. https://www.gfdrr.org/sites/default/files/publication/Final_PDNA_Evaluation_Report.pdf

75 **Rippey, B.R.** 2015. The U.S. drought of 2012. *Weather and Climate Extremes*, 10: 57–64. https://doi.org/10.1016/j.wace.2015.10.004

76 **Hamed, R., Vijverberg, S., Van Loon, A.F., Aerts, J. & Coumou, D.** 2023. Persistent La Niñas drive joint soybean harvest failures in North and South America. *Earth System Dynamics*, 14(1): 255–272. https://doi.org/10.5194/esd-14-255-2023

77 **Khor, J.F., Ling, L., Yusop, Z., Tan, W.L., Ling, J.L. & Soo, E.Z.X.** 2021. Impact of El Niño on Oil Palm Yield in Malaysia. *Agronomy*, 11(11): 2189. https://doi.org/10.3390/agronomy11112189

78 **Wang, J., Vanga, S., Saxena, R., Orsat, V. & Raghavan, V.** 2018. Effect of Climate Change on the Yield of Cereal Crops: A Review. *Climate*, 6(2): 41. https://doi.org/10.3390/cli6020041

79 **Oskorouchi, H.R. & Sousa-Poza, A.** 2021. Floods, food security, and coping strategies: evidence from Afghanistan. *Agricultural Economics*, 52(1): 123–140. https://doi.org/10.1111/agec.12610.

80 **D'Souza, A. & Jolliffe, D.** 2012. Rising food prices and coping strategies: Household-level evidence from Afghanistan. *Journal of Development Studies*, 48(2): 282–299. https://doi.org/10.1080/00220388.2011.635422

81 **Boyer, J.S., Byrne, P., Cassman, K.G., Cooper, M., Delmer, D., Greene, T., Gruis, F., Habben, J., Hausmann, N., Kenny, N., Lafitte, R., Paszkiewicz, S., Porter, D., Schlegel, A., Schussler, J., Setter, T., Shanahan, J., Sharp, R.E., Vyn, T.J., Warner, D. & Gaffney, J.** 2013. The U.S. drought of 2012 in perspective: A call to action. *Global Food Security*, 2(3): 139–143. https://doi.org/10.1016/j.gfs.2013.08.002

82 **Grande, F., Ueda, Y., Masangwi, S. & Holmes, B.** 2024. *Global nutrient conversion table for FAO supply utilization accounts*. Rome, FAO. https://doi.org/10.4060/cc9678en

83 **Institute of Medicine.** 1998. *Dietary reference intakes for thiamin, riboflavin, niacin, vitamin B6, folate, vitamin B12, pantothenic acid, biotin, and choline*. Washington, DC, The National Academies Press. https://doi.org/10.17226/6015

84 **Institute of Medicine.** 2000. *Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids*. Washington, DC, The National Academies Press. https://doi.org/10.17226/9810

85 **Institute of Medicine.** 2001. *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc*. Washington, DC, The National Academies Press. https://doi.org/10.17226/10026

86 **Institute of Medicine**. 2006. *Dietary Reference Intakes: The Essential Guide to Nutrient Requirements*. Washington, DC: The National Academies Press.

87 **FAO & WHO.** 2004. *Human vitamin and mineral requirements*. Report of a joint FAO/WHO expert consultation, Bangkok, Thailand. Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/y2809e

88 **FAO.** 2024. *The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action*. Rome. https://doi.org/10.4060/cd0683en

89 **FAO.** 2023. *The Impact of Disasters on Agriculture and Food Security 2023 – Avoiding and reducing losses through investment in resilience*. Rome. https://doi.org/10.4060/cc7900en

90 **FAO.** 2013. *Guidelines for the fisheries and aquaculture sector on damage and needs assessments in emergencies*. Rome. https://www.fao.org/4/i3433e/i3433e.pdf

91 **Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C.J., Benthuysen, J.A.** *et al.* 2016. A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, 141: 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

92 **CSIRO, Hobday, A., Oliver, E., Sen Gupta, A., Benthuysen, J., Burrows, M., Donat, M. *et al.*** 2018. Categorizing and Naming Marine Heatwaves. *Oceanography*, 31(2). https://doi.org/10.5670/oceanog.2018.205

93 **Chen, Y., Su, H., Yan, X.-H., Zhang, H. & Wang, Y.** 2024. Global oceans suffer extreme heatwaves intensifying since the early 21st century: A new comprehensive index. *Ecological Indicators*, 162: 112069. https://doi.org/10.1016/j.ecolind.2024.112069

94 **Oliver, E.C.J., Donat, M.G., Burrows, M.T., Moore, P.J., Smale, D.A., Alexander, L.V., Benthuysen, J.A. *et al.*** 2018. Longer and more frequent marine heatwaves over the past century. *Nature Communications*, 9(1): 1324. https://doi.org/10.1038/s41467-018-03732-9

95 **Oliver, E.C.J., Benthuysen, J.A., Darmaraki, S., Donat, M.G., Hobday, A.J., Holbrook, N.J., Schlegel, R.W. & Sen Gupta, A.** 2021. Marine Heatwaves. *Annual Review of Marine Science*, 13(1): 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

96 **Smale, D.A., Wernberg, T., Oliver, E.C.J., Thomsen, M., Harvey, B.P., Straub, S.C., Burrows, M.T. *et al.*** 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, 9(4): 306–312. https://doi.org/10.1038/s41558-019-0412-1

97 **Kauppi, L. & Villnäs, A.** 2022. Marine heatwaves of differing intensities lead to distinct patterns in seafloor functioning. *Proceedings of the Royal Society B: Biological Sciences*, 289(1986): 20221159. https://doi.org/10.1098/rspb.2022.1159

98 **Evans, R., Lea, M. & Hindell, M.A.** 2021. Predicting the distribution of foraging seabirds during a period of heightened environmental variability. *Ecological Applications*, 31(5): e02343. https://doi.org/10.1002/eap.2343

99 **La Manna, G., Ronchetti, F., Perretti, F. & Ceccherelli, G.** 2023. Not only wide range shifts: Marine warming and heat waves influence spatial traits of a mediterranean common bottlenose dolphin population. *Estuarine, Coastal and Shelf Science*, 285: 108320. https://doi.org/10.1016/j.ecss.2023.108320

100 **Monteiro, M., De Castro, S.L.P., Marques, S.C., Freitas, R. & Azeiteiro, U.M.** 2023. An emergent treat: Marine heatwaves - Implications for marine decapod crustacean species - An overview. *Environmental Research*, 229: 116004. https://doi.org/10.1016/j.envres.2023.116004

101 **Hartog, J.R., Spillman, C.M., Smith, G. & Hobday, A.J.** 2023. Forecasts of marine heatwaves for marine industries: Reducing risk, building resilience and enhancing management responses. *Deep Sea Research Part II: Topical Studies in Oceanography*, 209: 105276. https://doi.org/10.1016/j.dsr2.2023.105276

102 **Hayashida, H., Matear, R.J. & Strutton, P.G.** 2020. Background nutrient concentration determines phytoplankton bloom response to marine heatwaves. *Global Change Biology*, 26(9): 4800–4811. https://doi.org/10.1111/gcb.15255

103 **Schaeffer, A. & Roughan, M.** 2017. Subsurface intensification of marine heatwaves off southeastern Australia: The role of stratification and local winds. *Geophysical Research Letters*, 44(10): 5025–5033. https://doi.org/10.1002/2017GL073714

104 **Ding, Q., Chen, X., Hilborn, R. & Chen, Y.** 2017. Vulnerability to impacts of climate change on marine fisheries and food security. *Marine Policy*, 83: 55–61. https://doi.org/10.1016/j.marpol.2017.05.011

105 **Bahri, T., Vasconcellos, M., Welch, D.J., Johnson, J., Perry, R.I., Ma, Y. & Sharma, R., eds.** 2021. *Adaptive management of fisheries in response to climate change*. FAO. https://doi.org/10.4060/cb3095en

106 **Finger, R.** 2023. Digital innovations for sustainable and resilient agricultural systems. *European Review of Agricultural Economics*, 50(4): 1277–1309. https://doi.org/10.1093/erae/jbad021

107 **Global Commission on Adaptation.** 2019. *Adapt now: A global call for leadership on climate resilience*. Rotterdam, Global Center on Adaptation. https://openknowledge.worldbank.org/server/api/core/bitstreams/4d8d5979-ed31-5d22-977c-2c838b1732c5/content

108 **Trendov, N.M., Varas, S. & Zeng, M.** 2019. *Digital technologies in agriculture and rural areas: Briefing paper*. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/885161de-dccf-4589-8376-07fe37b68799/content

109 **FAO.** 2021. *Empowering smallholder farmers to access digital agricultural extension and advisory services*. Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/cb5944en

110 **FAO.** 2023. *Guide on digital agricultural extension and advisory services*. Rome, FAO. https://doi.org/10.4060/cc4022en

111 **WFP.** 2024. Insights and key trends. In: VAM *DataViz*. [Cited 15 September 2025]. https://dataviz.vam.wfp.org/insight-key-trends

112 **WFP.** 2025. Hunger map. In: *Hunger Map*. [Cited 15 September 2025]. https://hungermap.wfp.org

113 **Risk Data Library.** 2023. Risk data is for everyone: Open data, standard, and tools to act on disaster and climate risk in the most vulnerable countries. In: *Risk Data Library*. [Cited 15 September 2025]. https://riskdatalibrary.org

114 **UNDRR.** 2024. Exploring and enhancing data on non-economic losses. 24 October 2024. In: *UNDRR Updates*. [Cited 15 September 2025]. https://www.undrr.org/news/exploring-and-enhancing-data-non-economic-losses

115 **UNDRR.** 2023. Workshop on assessing the impact of slow-onset events. In: *UNDRR Events and Meetings*. [Cited 15 September 2025]. https://www.undrr.org/quick/80567

116 **Lam, R., Sanchez-Gonzalez, A., Willson, M., Wirnsberger, P., Fortunato, M., Alet, F., Ravuri, S. *et al.*** 2023. Learning skillful medium-range global weather forecasting. *Science*, 382(6677): 1416–1421. https://doi.org/10.1126/science.adi2336

117 **Pathak, J., Subramanian, S., Harrington, P., Raja, S., Chattopadhyay, A., Mardani, M., Kurth, T. *et al.*** 2022. *FourCastNet: A Global Data-driven High-resolution Weather Model using Adaptive Fourier Neural Operators*. arXiv:2202.11214. arXiv. [Cited 15 September 2025]. http://arxiv.org/abs/2202.11214

118 **OpenForis.** 2025. Open Foris: Free open-source solutions for forest and land monitoring. [Cited 15 September 2025]. https://openforis.org

119 **FAO.** 2020. *FAO's Hand-in-Hand Initiative: A new approach*. FAO Regional Conference for Africa, No. 31, ARC/20/2 Rev. 1. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/0bbb7e4f-1a1b-4364-a55d-d680d138b39e/content

120 **FAO.** 2025. CRTB: Climate Risk Tool Box. In: *FAO*. [Cited 15 September 2025]. https://www.fao.org/agroinformatics/projects/projects-detail/fao-climate-risk-toolbox-(crtb)/en

121 **FAO.** 2022. *Framework for Environmental and Social Management*. FAO. https://doi.org/10.4060/cb9870en

122 **FAO.** 2023. *Climate Risk Toolbox – Guiding material for climate risk screening*. FAO. https://doi.org/10.4060/cc2909en

123 **Intergovernmental Panel On Climate Change (Ipcc).** 2023. *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. First edition. Cambridge University Press. https://doi.org/10.1017/9781009325844

124 **Climate Centre (RCCC).** 2020. *The future of forecasts: Impact-based forecasting for early action*. Red Cross Red Crescent Movement. https://www.anticipation-hub.org/Documents/Manuals_and_Guidelines/RCCC_Impact_based_forecasting_Guide_2021-3.pdf

125 **Adounkpe, P., Ghosh, S. & Amarnath, G.** 2022. *Multi-hazard risk mapping with machine learning*. CGIAR Climate Resilience Initiative. https://cgspace.cgiar.org/server/api/core/bitstreams/18e0f853-81ae-4ef6-950e-8d1c1b744a6e/content

126 **FAO.** 2025. FAO Soils Portal. In: FAO. [Cited 15 September 2025]. https://www.fao.org/soils-portal/en/

127 **Strauss, T., El Fali, I. & Gomez, P.** 2024. Ground zero: Why soil health is integral to beating climate change. 22 November 2024. In: *World Economic Forum*. [Cited 15 September 2025]. https://www.weforum.org/stories/2024/11/soil-climate-change-sustainable-agriculture/

128 **Soriano-Disla, J.M., Janik, L.J., Viscarra Rossel, R.A., Macdonald, L.M. & McLaughlin, M.J.** 2014. The Performance of Visible, Near-, and Mid-Infrared Reflectance Spectroscopy for Prediction of Soil Physical, Chemical, and Biological Properties. *Applied Spectroscopy Reviews*, 49(2): 139–186. https://doi.org/10.1080/05704928.2013.811081

129 **FAO.** 2025. SoilFER: Soil mapping for resilient agrifood systems. In: *Global Soil Partnership*. [Cited 15 September 2025]. https://data.apps.fao.org/soilfer/?lang=en

130 **Ali, T.** 2023. Farmspace – A low-cost AI-powered soil testing device. 5 November 2023. In: *Climate Adaptation & Low-Carbon Housing Challenge*. [Cited 15 September 2025]. https://solve.mit.edu/solutions/75872

131 **SoilOptix.** 2025. SoilOptix. [Cited 15 September 2025]. https://soiloptix.com

132 **Innovative Solutions for Decision Agriculture (iSDA).** 2025. Expert advice for every farmer. Delivered by AI. [Cited 15 September 2025]. https://www.isda-africa.com

133 **Innovative Solutions for Decision Agriculture (iSDA).** 2025. Virtual agronomist. [Cited 15 September 2025]. https://www.isda-africa.com/virtual-agronomist/

134 **FAO.** 2025. One Health. In: *FAO*. [Cited 15 September 2025]. https://www.fao.org/one-health/areas-of-work/water/en

135 **MARVI.** 2025. MARVI: Managing aquifer recharge and sustaining groundwater use through village-level intervention. [Cited 15 September 2025]. https://www.marvi.org.in

136 **GEO Aqua Watch.** 2024. Project spotlight: CERTO. In: *GEO Aqua Watch*. [Cited 15 September 2025]. https://www.geoaquawatch.org

137 **IBM.** 2018. IBM researchers in Africa helping to harness safe water for remote parts of Kenya. [Cited 15 September 2025]. https://mea.newsroom.ibm.com/2018-08-29-IBM-Researchers-in-Africa-Helping-to-Harness-Safe-Water-for-Remote-Parts-of-Kenya

138 **FAO.** 2024. WaPOR: Remote sensing for water productivity. In: *FAO*. [Cited 15 September 2025]. https://www.fao.org/in-action/remote-sensing-for-water-productivity/en/

139 **WMO.** 2024. Empowering farmers: The role of agrometeorological services in sustainable agriculture. 29 July 2024. In: *World Meteorological Organization*. [Cited 15 September 2025]. https://wmo.int/media/update/empowering-farmers-role-of-agrometeorological-services-sustainable-agriculture

140 **FAO.** 2021. Agrometeorological information for resilient agrifood systems. 23 March 2021. In: *FAO*. [Cited 15 September 2025]. https://www.fao.org/climate-change/news/news-detail/Agrometeorological-information-for-resilient-agri-food-systems/en

141 **K V, M., Maiti, S., Garai, S., Reddy, D.A.K., Sahani, S., Panja, A. & Jha, S.K.** 2024. Impact of climate services on the operational decision and economic outcome of wheat (Triticum aestivum) and rice (Oryza sativa) cultivation in Haryana. *The Indian Journal of Agricultural Sciences*, 94(3–1): 116–123. https://doi.org/10.56093/ijas.v94i3.148633

142 **Nannewar, R.G., Kanitkar, T. & Srikanth, R.** 2023. Role of Agrometeorological Advisory Services in Enhancing Food Security and Reducing Vulnerability to Climate Change. *Weather, Climate, and Society*, 15(4): 1013–1027. https://doi.org/10.1175/WCAS-D-22-0130.1

143 **Dupdal, R., Dhakar, R., Rao, C.A.R., Samuel, J., Raju, B.M.K., Kumar, P.V. & Rao, V.U.M.** 2021. Farmers' perception and economic impact assessment of agromet advisory services in rainfed regions of Karnataka and Andhra Pradesh. *Journal of Agrometeorology*, 22(3): 258–265. https://doi.org/10.54386/jam.v22i3.187

144 **Bizo, I.M., Traore, B., Sidibé, A. & Soulé, M.** 2024. Effectiveness of climate information services: An evaluation of the accuracy and socio-economic benefits for smallholder farmers in Niger and Mali. *Frontiers in Climate*, 6: 1345888. https://doi.org/10.3389/fclim.2024.1345888

145 **Seydou, T.H., Agali, A., Aissatou, S., Seydou, T.B., Issaka, L. & Ibrahim, B.M.** 2023. Evaluation of the impact of seasonal agroclimatic information used for early warning and farmer communities' vulnerability reduction in southwestern Niger. *Climate*, 11(2): 31. https://doi.org/10.3390/cli11020031

146 **Tarchiani, V., Coulibaly, H., Baki, G., Sia, C., Burrone, S., Nikiema, P.M., Migraine, J.-B. & Camacho, J.** 2021. Access, uptake, use and impacts of agrometeorological services in Sahelian rural areas: The case of Burkina Faso. *Agronomy*, 11(12): 2431. https://doi.org/10.3390/agronomy11122431

147 **FAO**. 2022. *The future of food and agriculture – Drivers and triggers for transformation*. The Future of Food and Agriculture, no. 3. Rome. https://doi.org/10.4060/cc0959en

148 **FAO**. 2024. *The Smart Extension and Efficient Decision-making (S.E.E.D.)* Hub [video]. 2 May 2024. [Cited 15 September 2025]. https://www.youtube.com/watch?v=0UtaddB0Y00

149 **Digital Green.** 2024. Cultivating knowledge: Bridging agriculture, technology and indigenous wisdom. 23 February 2024. In: *Video-based extension*. [Cited 15 September 2025]. https://digitalgreen.org/tag/video-based-extension/

150 **Farm Radio International.** 2025. Uliza: Listener interactivity services. [Cited 15 September 2025]. https://farmradio.org/uliza-services/

151 **Kuza.** 2025. Revolutionising rural business. [Cited 15 September 2025]. https://www.kuza.one

152 **FAO.** 2025. Navigate digital agriculture developments in Europe and Central Asia. In: *AgriTech Observatory*. [Cited 15 September 2025]. https://agritechobservatory.fao.org/analytics

153 **Digital Agri Hub.** 2025. Dashboard. In: *Digital Agri Hub*. [Cited 15 September 2025]. https://digitalagrihub.org/web/guest/dashboardframe

154 **Mhlanga, D. & Ndhlovu, E.** 2023. Digital technology adoption in the agriculture sector: Challenges and complexities in Africa. *Human Behaviour and Emerging Technologies*, 2023(1): 6951879. https://doi.org/10.1155/2023/6951879

155 **J.R., Parida T.C., Limnirankul, B., Kramol, P., Hoang Gia, H. & Nguyen Thi, D.T.** 2025. Digital technology adoption among smallholder farmers in Viet Nam: Implications for digital agricultural extension strategies. *Journal of International Development*, 37(2): 351–370. https://doi.org/10.1002/jid.3904

156 **WMO.** 2020. *State of Climate Services: Risk information and early warning systems*. WMO-No. 1252. Geneva, WMO. [Cited 15 September 2025]. https://library.wmo.int/idurl/4/57191

157 **EW4ALL.** 2025. Early Warnings for All. [Cited 15 September 2025]. https://earlywarningsforall.org/

158 **Knight-Jones, T.J.D. & Rushton, J.** 2013. The economic impacts of foot and mouth disease – What are they, how big are they and where do they occur? *Preventive Veterinary Medicine*, 112(3–4): 161–173. https://doi.org/10.1016/j.prevetmed.2013.07.013

159 **Pirbright Institute.** 2025. FMDbase. In: *FMDbase*. [Cited 15 September 2025]. https://www.fmdbase.org

160 **The Pirbright Institute.** 2025. FMDtype. In: *FMDtype*. [Cited 15 September 2025]. https://openfmd.org/dashboard/fmdtype/#!/upload_data

161 **Epi-interactive.** 2025. FMDwatch. In: *FMDwatch*. [Cited 15 September 2025]. https://www.openfmd.org/dashboard/fmdwatch/

162 **Epi-interactive.** 2025. PRAGMATIST. In: *OpenFMD*. [Cited 15 September 2025]. https://www.openfmd.org/dashboard/pragmatist/

163 **FAO.** 2025. FAW presence monitoring from scouting and traps. In: *Fall Armyworm (FAW) Monitoring & Early Warning System*. Rome, FAO. [Cited 15 September 2025]. https://app.powerbi.com/view?r=eyJrIjoiMGQ3MzEwMTctMTlhOC00YzM3LTkxNTgtOWIxYjIwN2YyNjFlIiwidCI6IjE2M2FjNDY4LWFiYjgtNDRkMC04MWZkLWQ5ZGIxNWUzYWY5NiIsImMiOjh9

164 **Plant Village.** 2025. We help smallholder farmers across Africa, Asia and the Americas adapt to climate change. In: *Plant Village*. [Cited 15 September 2025]. https://plantvillage.psu.edu

165 **Guimapi, R.A., Niassy, S., Mudereri, B.T., Abdel-Rahman, E.M., Tepa-Yotto, G.T., Subramanian, S., Mohamed, S.A. *et al.*** 2022. Harnessing data science to improve integrated management of invasive pest species across Africa: An application to Fall armyworm (Spodoptera frugiperda)(J.E. Smith)(Lepidoptera: Noctuidae). *Global Ecology and Conservation*, 35: e02056. https://doi.org/10.1016/j.gecco.2022.e02056

166 **O'Neill, L., Gubbins, S., Reynolds, C., Limon, G. & Giorgakoudi, K.** 2024. The socioeconomic impacts of Rift Valley fever: A rapid review. *PLOS Neglected Tropical Diseases*, 18(8): e0012347. https://doi.org/10.1371/journal.pntd.0012347

167 **Mariner, J.** 2018. *Rift Valley fever surveillance*. FAO Animal Production and Health. Rome, FAO. https://openknowledge.fao.org/items/72e85c3a-cb75-436f-8cdd-b7d09f1f11d0

168 **Mariner, J. C., Raizman, E., Pittiglio, C., Bebay, C., Kivaria, F., Lubroth, J., & Makonnen, Y.** 2022. *Rift Valley fever action framework*. FAO. https://doi.org/10.4060/cb8653en

169 **Martin, V., Chevalier, V., Ceccato, P., Anyamba, A., De Simone, L., Lubroth, J., de La Rocque, S. & Domenech, J.** 2008. The impact of climate change on the epidemiology and control of Rift Valley fever. *Revue Scientifique et Technique de l'Office International des Epizooties*, 27(2): 413–426. https://doi.org/10.20506/rst.27.2.1802

170 **FAO.** 2021. *Driving preparedness and anticipatory actions through innovation: A web-based Rift Valley fever Early Warning Decision Support Tool*. Rome. https://www.fao.org/3/cb5875en/cb5875en.pdf

171 **Pittiglio, C., Kivaria, F., Morteo, K., Bebay, C., Seck, I., Falcucci, A., Cinardi, G. *et al.*** 2024. *Real-time disease risk monitoring and forecasting for early action*. In: *2024 12th International Conference on Agro-Geoinformatics (Agro-Geoinformatics)*. 2024 12th International Conference on Agro-Geoinformatics (Agro-Geoinformatics), Novi Sad, Serbia, IEEE, 15 July 2024. https://doi.org/10.1109/Agro-Geoinformatics262780.2024.10661081

172 **Sang, R., Nguku, P.M., Britch, S.C., Reynes, J.-M., Mohamed, M.A., Formenty, P., Anyamba, A. *et al.*** 2010. Prediction, Assessment of the Rift Valley Fever Activity in East and Southern Africa 2006–2008 and Possible Vector Control Strategies. *The American Journal of Tropical Medicine and Hygiene*, 83(2_Suppl): 43–51. https://doi.org/10.4269/ajtmh.2010.09-0289

173 **Tran, A., Trevennec, C., Lutwama, J., Sserugga, J., Gély, M., Pittiglio, C., Pinto, J. & Chevalier, V.** 2016. Development and Assessment of a Geographic Knowledge-Based Model for Mapping Suitable Areas for Rift Valley Fever Transmission in Eastern Africa. *PLOS Neglected Tropical Diseases*, 10(9): e0004999. https://doi.org/10.1371/journal.pntd.0004999

174 **Anyamba, A., Chretien, J.-P., Small, J., Tucker, C.J., Formenty, P.B., Richardson, J.H., Britch, S.C. *et al.*** 2009. Prediction of a Rift Valley fever outbreak. *Proceedings of the National Academy of Sciences*, 106(3): 955–959. https://doi.org/10.1073/pnas.0806490106

175 **FAO & IGAD.** 2022. FAO and IGAD alert countries in Eastern Africa to remain vigilant for Rift Valley fever. 15 February 2022. Rome, FAO. https://www.fao.org/3/cb8651en/cb8651en.pdf

176 **IPC.** 2025. IPC overview and classification system. In: *IPCinfo.org*. [Cited 15 September 2025]. https://www.ipcinfo.org/ipcinfo-website/ipc-overview-and-classification-system/en/

177 **IPC Global Partners.** 2024. IPC overview and classification system. In: *Integrated Food Security Phase Classification*. [Cited 15 September 2025]. https://www.ipcinfo.org/ipcinfo-website/ipc-overview-and-classification-system/en/

178 **FAO.** 2023. Integrated Food Security Phase Classification. 22 February 2023. In: *FAO*. [Cited 15 September 2025]. https://www.fao.org/evaluation/highlights/detail/integrated-food-security-phase-classification/

179 **UNEP.** 2024. Strata: Visualising complex risks for informed action. In: *Geospatial Insights for a Changing World*. [Cited 15 September 2025]. https://strata.earthmap.org/

180 **FAO.** 2024. Agro-informatics Platform. In: *FAO*. [Cited 15 September 2025]. https://data.apps.fao.org/?lang=en

181 **GAIN & The Columbia Climate School.** 2024. Food Systems Dashboard. In: *Food Systems Dashboard*. [Cited 15 September 2025]. https://www.foodsystemsdashboard.org

182 **FAO.** 2025. *Agricultural Monitoring Platform for Sudan*. [Cited 15 September 2025]. https://tableau.apps.fao.org/views/FAOSudan/AgricultureMonitoringPlatform?:origin=card_share_link&:embed=n

183 **Barhy, A., Mukaratirwa, R., Jalal, R., Farren, F., Ghosh, A. Mohamed, A., AbdAllaElshekh, M., Adam, A., Warrag, A., Warrag, E., Ali, I., Igbokwe, K., Yao, A. and Henry, M.** 2024. *Geospatial cropland monitoring and crop type mapping of the Gezira irrigation scheme in the Sudan*. FAO. https://doi.org/10.4060/cd1386en

184 **FAO.** 2025. *Crop type mapping and crop production estimation in the Gezira Irrigation Scheme (2024/25)*. Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/cd6080en

185 **GEOGLAM.** 2025. About GEOGLAM. In: *GEOGLAM Global Agricultural Monitoring*. [Cited 15 September 2025]. https://earthobservations.org/geoglam.php

186 **WFP.** 2025. Economic Explorer – Overview. In: *Dataviz.VAM.WFP.org*. [Cited 15 September 2025]. https://dataviz.vam.wfp.org/economic/overview?current_page=1

187 **FAO.** 2025. FPMA: Food Price Monitoring and Analysis. In: *FAO*. [Cited 15 September 2025]. https://www.fao.org/giews/food-prices/home/en

188 **Silva E Silva, L., Mongeau Ospina, C.A. & Fabi, C.** 2024. Food price inflation nowcasting and monitoring. *Statistical Journal of the IAOS: Journal of the International Association for Official Statistics*, 40(2): 325–339. https://doi.org/10.3233/SJI-230083

189 **Google.** 2025. Flood Hub. In: *Sites.research.google*. [Cited 15 September 2025]. https://sites.research.google/floods/l/0/0/3

190 **Google.** 2025. Flood forecasting. In: *Sites.research.google*. [Cited 15 September 2025]. https://sites.research.google/gr/floodforecasting/

191 **Nearing, G., Cohen, D., Dube, V., Gauch, M., Gilon, O., Harrigan, S., Hassidim, A.** *et al.* 2024. Global prediction of extreme floods in ungauged watersheds. *Nature*, 627(8004): 559–563. https://doi.org/10.1038/s41586-024-07145-1

192 **WFP.** 2025. PRISM: Combining remote sensing and vulnerability data for risk and impact analytics. In: *Innovation Accelerator*. Rome, World Food Programme. [Cited 15 September 2025]. https://innovation.wfp.org/project/prism

193 **Sylvester, G., ed.** 2018. *E-agriculture in action: Drones for agriculture*. Bangkok, FAO and International Telecommunication Union. https://openknowledge.fao.org/handle/20.500.14283/i8494en

194 **WFP.** 2024. SKAI: Unleashing the power of artificial intelligence (AI) to revolutionize disaster response and humanitarian aid. 25 November 2024. In: *WFP Innovation Accelerator*. [Cited 15 September 2025]. https://innovation.wfp.org/project/SKAI

195 **Baha, A. & Morrell, H.** 2023. Revolutionizing disaster response with SKAI. 7 March 2023. In: *WFP Innovation Accelerator*. [Cited 15 September 2025]. https://wfpinnovation.medium.com/revolutionizing-disaster-response-with-skai-1ae9e02e87e5

196 **FAO.** 2024. WaPOR: Remote sensing for water productivity. In: *FAO*. [Cited 15 September 2025]. https://www.fao.org/in-action/remote-sensing-for-water-productivity/en/

197 **WFP.** 2025. Advanced Disaster Analysis and Mapping (ADAM). In: *WFP.org*. [Cited 15 September 2025]. https://gis.wfp.org/adam/

198 **FAO.** 2025. DIEM – Events Visualization in Emergencies (EVE). In: *FAO*. [Cited 15 September 2025]. https://data-in-emergencies.fao.org/pages/diem_eve

199 **NASA & Goddard Space Flight Centre.** 2025. Visible Infrared Imaging Radiometer Suite (VIIRS). In: *Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center.* [Cited 15 September 2025]. https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/viirs/

200 **ESA.** 2025. ESA WorldCover 2020: Global land cover product at 10 m resolution for 2020 based on Sentinel-1 and 2 data. [Cited 15 September 2025]. https://worldcover2020.esa.int

201 **Anticipatory Action Task Force.** n.d. Anticipatory action. [Cited 25 July 2025]. https://anticipatoryaction.org/

202 **FAO.** n.d. Somalia Water and Land Information Management (SWALIM). [Cited 25 July 2025]. https://www.faoswalim.org/

203 **FAO.** 2021. *Protecting livelihoods – Linking agricultural insurance and social protection.* Rome. https://doi.org/10.4060/cb2690en

204 **IFC Advisory Services.** n.d. Kilimo Salama – Index-based agriculture insurance. In: *IFC / Ideas.* [Cited 15 September 2025]. https://documents1.worldbank.org/curated/ru/963291468039041424/pdf/947940WP0Box380ture0Insurance0Final.pdf

205 **Benni, N.** 2023. *Fintech innovation for smallholder agriculture – A review of experiences.* Rome, FAO. https://doi.org/10.4060/cc9117en

206 **Dhingra, M.** 2023. *Livestock Investment Coordination System (LICS).* Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/f4ad71c9-2edc-46ac-96c5-e9b2a2ad89a4/content

207 **World Bank.** 2023. *Using disaster risk financing to build adaptive social protection for climate shocks in Malawi: Social support for resilient livelihoods* [brief]. Washington, DC. http://hdl.handle.net/10986/40680

208 **Sylvester, G., ed.** 2018. *E-agriculture in action: Drones for agriculture.* Bangkok, FAO and International Telecommunication Union. https://openknowledge.fao.org/handle/20.500.14283/i8494en

209 **FAO.** 2025. Agricultural Monitoring Platform for Sudan. [Cited 15 September 2025]. https://tableau.apps.fao.org/views/FAOSudan/AgricultureMonitoringPlatform?:origin=card_share_link&:embed=n

210 **Fatouros, S. & Capetola, T.** 2021. Examining Gendered Expectations on Women's Vulnerability to Natural Hazards in Low to Middle Income Countries: A critical Literature Review. *International Journal of Disaster Risk Reduction*, 64: 102495. https://doi.org/10.1016/j.ijdrr.2021.102495

211 **ReefScan.** n.d. Innovating for life below water – and people who matter. In: *ReefScan.* Brisbane, Australia, ReefScan. [Cited 28 July 2025]. https://www.reefscan.org

212 **UNESCO.** 2021. *Recommendation on the ethics of artificial intelligence.* Paris, UNESCO. [Cited 1 August 2025]. https://unesdoc.unesco.org/ark:/48223/pf0000381137

213 **United Nations Office for Disaster Risk Reduction (UNDRR).** n.d. *PreventionWeb.* [Cited 1 August 2025]. https://www.preventionweb.net/

214 **United Nations Office for the Coordination of Humanitarian Affairs (OCHA).** n.d. *ReliefWeb.* [Cited 1 August 2025]. https://reliefweb.int/

215 **World Bank.** n.d. *Global Facility for Disaster Reduction and Recovery.* [Cited 1 August 2025]. https://www.gfdrr.org/en

216 **World Bank.** n.d. *World Bank.* [Cited 1 August 2025]. https://www.worldbank.org/

217 **Centre for Research on the Epidemiology of Disasters (CRED).** n.d. *EM-DAT: The International Disaster Database.* [Cited 1 August 2025]. https://www.emdat.be/

218 **FAO.** n.d. *FAOSTAT.* [Cited 1 August 2025]. https://www.fao.org/faostat

219 **United States Department of Agriculture (USDA).** n.d. *United States Department of Agriculture.* [Cited 1 August 2025]. https://www.usda.gov/

220 **Izakian, H., Pedrycz, W. & Jamal, I.** 2015. Fuzzy clustering of time series data using dynamic time warping distance. *Engineering Applications of Artificial Intelligence*, 39: 235–244. https://doi.org/10.1016/j.engappai.2014.12.015

221 **Pagès, J.** 2014. *Multiple Factor Analysis by Example Using R*. First edition. Chapman and Hall/CRC. https://doi.org/10.1201/b17700

222 **Grande, F., Ueda, Y., Masangwi, S. & Holmes, B.** 2024. *Global nutrient conversion table for FAO supply utilization accounts*. Rome, FAO. https://doi.org/10.4060/cc9678en

223 **FAO.** 2022. *The future of food and agriculture – Drivers and triggers for transformation*. The Future of Food and Agriculture, No. 3. Rome. https://doi.org/10.4060/cc0959en

224 **FAO.** 2023. *The State of Food and Agriculture 2023 – Revealing the true cost of food to transform agrifood systems*. Rome. https://doi.org/10.4060/cc7724en

225 **IPCC.** 2021. Summary for policymakers. In: *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 423–553. Cambridge, UK, and New York, USA, Cambridge University Press. https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf

226 **United Nations.** 1992. *United Nations Framework Convention on Climate Change*. Article 1. [Cited 1 August 2025]. https://unfccc.int/resource/ccsites/zimbab/conven/text/art01.htm

227 **General Assembly of the United Nations.** 2017. *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. Seventy-first session, agenda item 19 (c) Sustainable development: disaster risk reduction. New York, USA, United Nations. https://reliefweb.int/report/world/2022-disasters-numbers

228 **FAO.** n.d. *Digital solutions listing*. [Cited 1 August 2025]. https://dvi-ke.fao.org/digital_solutions_listing.php?page=30

229 **FAO.** 2020. *The State of Agricultural Commodity Markets 2020. Agricultural markets and sustainable development: Global value chains, smallholder farmers and digital innovations*. Rome. https://doi.org/10.4060/cb0665en

230 **United Nations Office for Disaster Risk Reduction (UNDRR).** 2017. *The Sendai Framework terminology on disaster risk reduction: Disaster risk management*. [Cited 31 July 2025]. https://www.undrr.org/terminology/disaster-risk-management

231 **The Nansen Initiative.** 2015. *The Nansen Initiative: Global consultation. Conference report, Geneva, 12–23 October 2015*. Bern, Federal Department of Foreign Affairs of Switzerland. https://www.eda.admin.ch/dam/eda/en/documents/aussenpolitik/menschenrechte-menschliche-sicherheit/2017-und-aelter/Nansen-GCR2015-screen.pdf

232 **FAO, IFAD, UNICEF, WFP and WHO**. 2022. *The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable*. Rome, FAO. https://doi.org/10.4060/cc0639en

233 **IPCC.** 2022. Annex II: Glossary [Möller, V., van Diemen, R., Matthews, J.B.R., Méndez, C., Semenov, S., Fuglestvedt, J.S., & Reisinger, A., eds.]. In: *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Okem, A. & Rama, B., eds.], pp. 2897–2930. Cambridge, UK, and New York, USA, Cambridge University Press. https://doi.org/10.1017/9781009325844.029

2025
THE IMPACT OF
DISASTERS ON AGRICULTURE AND FOOD SECURITY
DIGITAL SOLUTIONS FOR REDUCING RISKS AND IMPACTS

Agriculture and food security face unprecedented challenges from the escalating frequency and intensity of disasters worldwide. This report provides a comprehensive analysis of how disasters disrupt agricultural systems across multiple dimensions – from immediate production losses to cascading effects through infrastructure, markets, financial systems, and ecosystem services. It examines the complex pathways through which hazards affect crops, livestock, fisheries, and aquaculture, while highlighting critical gaps in current assessment methodologies that do not capture the full spectrum of impacts, including non-economic losses, differentiated effects on at-risk groups, and long-term consequences for vulnerable communities.

Alongside documenting these mounting challenges, the report charts a transformative path forward through digital innovation. It demonstrates how emerging technologies – from satellite monitoring and artificial intelligence to mobile advisory services and predictive analytics – are revolutionizing disaster risk management in agriculture. Through case studies and practical examples, the analysis reveals how digital solutions enable the shift from reactive response to proactive prevention, supporting early warning systems, anticipatory action, and resilience building. Emphasizing that technology alone cannot drive change, the report underscores the critical importance of human-centred design, institutional capacity, enabling policy frameworks, and diverse partnerships to ensure that digital transformation serves the needs of smallholder farmers and vulnerable communities most exposed to disaster risks.

ISBN 978-92-5-140180-4

9 789251 401804

CD7185EN/1/11.25