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THE STATE OF THE WORLD'S LAND AND WATER RESOURCES FOR FOOD AND AGRICULTURE

THE POTENTIAL TO PRODUCE MORE AND BETTER

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COVER PHOTOGRAPH © Quang Nguyen Vinh

VIET NAM. A lone farmer walks between rice paddy fields in Yen Bai.

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Food and Agriculture Organization of the United Nations
Rome, 2025

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FOREWORD

Land, soil and water resources are the foundations for agricultural production and global food security. By 2050, the global population is projected to reach 9.7 billion, and agriculture will need to produce around 50 percent more food, feed and fibre than in 2012. Meeting this demand will place additional pressure on resources that are already under severe strain: over 60 percent of human-induced land degradation occurs on agricultural lands (including cropland and pastureland), and agriculture accounts for more than 70 percent of global freshwater withdrawal. With 95 percent of food produced on land, the combined threats of land degradation, water scarcity and weather extremes pose significant challenges to agrifood systems, livelihoods, and biodiversity.

This third edition of *The State of the World's Land and Water Resources for Food and Agriculture* examines how we can produce more, and better, while safeguarding the world's finite resources. It focuses on the potential of major cultivated crops – both now and under future climate scenarios – and on the policies, practices and technologies that can help close yield gaps sustainably.

While past gains in agricultural production and productivity have been able to keep pace with the increasing needs of a rapidly growing population, mainly through intensification, these achievements have often come at a high environmental and social cost.

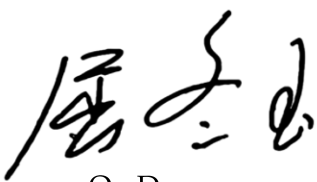
In many regions, food security and agrifood systems are at risk. Yet solutions exist. Sustainable agricultural practices can counter this risk by restoring land, soil and water resources and by generating valuable ecosystem benefits. In parallel, sustainable management of land, soil and water resources can significantly mitigate the effects of – and strengthen adaptation to – climate change.

Future gains must come from smarter – not just increased – food production, by closing yield gaps, diversifying the selection of suitable and resilient crops, and applying locally adapted, resource-efficient practices suited to land, soil and water conditions. There is no single pathway, no one-size-fits-all solution.

The report explores practical options for sustainable land, soil and water use and management. It presents actions and solutions, illustrated with examples, and identifies the key enablers required to scale them up for lasting and sustained impact and to make our agrifood systems more efficient, inclusive, resilient and sustainable.

FAO's work on land, soil and water resources, guided by the FAO Conceptual Framework for Integrated Land and Water Resources Management, supports Members in developing policies, programmes, best practices and management tools that ensure productive and efficient use of land, soil and water resources.

I invite you to explore this edition of *The State of the World's Land and Water Resources for Food and Agriculture*, and to join us in transforming agrifood systems for better production, better nutrition, a better environment and a better life for all, leaving no one behind. The choices we make today for the management of land and water resources will determine how we meet current and future demands while protecting the world for generations to come.



Qu Dongyu
FAO Director-General

METHODOLOGY

The first edition of *The State of the World's Land and Water Resources for Food and Agriculture*, published in 2011, presented up-to-date and comprehensive information and analyses on the global state, trends and challenges of land and water resources. The 2011 edition also elaborated on options and strategies for addressing evolving issues such as water scarcity and land degradation.

The second edition, published in 2021, provided an update of the knowledge base, accompanied by a suite of related recommendations and actions for decision-makers.

This 2025 edition of *The State of the World's Land and Water Resources for Food and Agriculture* focuses on the hidden and untapped potential of land and water resources to enhance sustainable agricultural production for main crops and food security. While the report looks at land and water in an integrated way, considering crops, rangeland, fisheries and aquaculture, as well as forests, particular attention is paid to crops through a thorough analysis of main crop production potential based on data and information derived from version 5 of the Global Agro-Ecological Zoning (GAEZ) assessment co-led by FAO and the International Institute for Applied Systems Analysis (IIASA).

Chapter 1 provides an overview of the challenges affecting land, soil and water resources, before Chapter 2 presents the status of land, soil and water resources based on a literature review and focused analysis, using data from FAO and other sources. Chapter 3 describes and discusses the results of the GAEZ-based analysis, showing land's suitability for main crops now and under future climate scenarios, assuming high-level input management. The methodology used in this analysis is also presented in Chapter 3 and further detailed in the Annex. The analysis focuses on soil, terrain and climatic conditions, without consideration of socioeconomic and ecological factors directly affecting potential production. However, it also provides information to support decisions on the overall geographical distribution of suitability for main crops and recommends options and actions for the sustainable use and management of land and water resources, leveraging key data and knowledge critical to supporting and informing policymaking at all levels. Chapter 3 also describes the yield gaps for main crops. Narrowing the yield gap using sustainable management options will increase food production. Examples of sustainable management options and an enabling environment to narrow the yield gap are discussed in Chapter 4 and Chapter 5.

Recognizing that there is no one-size-fits-all solution, the report recommends some technical options and actions for the sustainable use and management of land and water resources (see Chapter 4) and discusses the enabling conditions for such actions to be adopted by land users and scaled up (see Chapter 5).

This latest edition of *The State of the World's Land and Water Resources for Food and Agriculture* targets policymakers, decision-makers, experts and practitioners from government and non-governmental organizations, academia and research, producers' organizations and the private sector; it promotes the sustainable use and management of land, soil and water resources to enable the transformation of agrifood systems to become more efficient, more resilient and more sustainable.

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Overall supervision and review:
L. Li, N. Berrahmouni.

Coordination:
F. Ziadat.

Authors:
R. Arthur, E. Barrios, N. Berrahmouni, D. Bojic, R. Boroto, A. Bres, S. Casallas Ramirez, F. Chiozza, G. Conchedda, V. Crespi, J-M. Faurès, A. Grobicki, J. Hoogeveen, J. Jorgensen, K. Khazal, B. Kiersch, M. Konyushkova, A. Lemaitre, L. Li, F. Marttin, G. Munoz, C. Olivera Sanchez, L. Peiser, N. Rodriguez Eugenio, M. Salman, G. Santini, Y. Tong, A. Vollrath, X. Wang, D. Wisser, Y. Yigini, T. Zambrana, F. Ziadat.

Contributors:
V. Agostini, W. Ahmad, F. Boerstler, B. De Ridder, C. Del Campo Aragones, D. Fallas Conejo, N. Franz, R. Ito, A. Lovatelli, L. Magliocchetti Lombi, G. Mair, E. Pek, N. Rakotovao, M. Sacande, E. Springgay, A. Yepes Quintero.

Technical editing:
J.M. Faures.

External and internal technical reviewers (chapter reviewers):
O. Andreeva, A. Arslan, M. Barange, E. Barrios, M. Bernoux, F. Castell, A. Cattaneo, M. Chaya, B. Crawford, B. Dazis, A. Duchelle, M. Felix, D. Fernandez Reguera, A. Glinni, D. Gutierrez Mendez, J. Herrick, D. Laborde, X. Liangjie, R. Mc Donnell, A. Meybeck, H. Muminjanov, F. Nachtergaele, B.J. Orr, C. Pereira, L. Philips, F. Pierri, M. Sanchez Cantillo, D. Syme, V. Tandon, T. Walfram Petursdottir, A. Ward, Z. Wu, L. Xin, Y. Yasmi.

Process facilitation:
K. Khazal, F. Ziadat.

Language and copy-editing:
C. Pedrick and the Publications and Library Branch of the FAO Office of Communications.

Preparation of statistics and maps:
F. Chiozza, G. Conchedda, K. Khazal.

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ABBREVIATIONS

AQUASTAT	Global Information System on Water and Agriculture
ASIS	Agricultural Stress Index System
BMPs	best management practices
CA	conservation agriculture
CAM	Cropland Agreement Map
CI	cropping intensity
CBD	Convention on Biological Diversity
ComDev	Communication for Development
COP	Conference of the Parties
CSB	climate-smart business
DRR	disaster risk reduction
DSL-IP	Sustainable Forest Management Impact Program on Dryland Sustainable Landscapes
EAA	ecosystem approach to aquaculture
EAF	ecosystem approach to fisheries
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Corporate Database for Substantive Statistical Data
FFF	Forest and Farm Facility
FFS	Farmer Field School
FLID	Farmer-Led Irrigation Development
FLR	forest and landscape restoration
GAEZ	Global Agro-Ecological Zoning
GBF	Kunming-Montreal Global Biodiversity Framework
GDP	gross domestic product
GEF	Global Environment Facility
GHG	greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
IIASA	International Institute for Applied Systems Analysis
ILM	integrated landscape management
ILUP	integrated land-use planning
IPCC	Intergovernmental Panel on Climate Change
IWRM	integrated water resources management
LDN	land degradation neutrality
NPOA-SSF	National Plan of Action for Sustainable Small-Scale Fisheries (Uganda)
NWFP	non-wood forest product
PILA	Participatory Informed Landscape Approach
PLF	precision livestock farming
PRISM	Prioritization of Irrigation Schemes for Modernization/Rehabilitation
RCP	Representative Concentration Pathway
RFID	radio frequency identification
SDG	Sustainable Development Goal
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SHARP+	Self-evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists
SLM	sustainable land management
SLPF	Sustainable Landscape Production Framework

ABBREVIATIONS

SSF Guidelines	Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication
SSP	Shared Socioeconomic Pathway
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
UPA	urban and peri-urban agriculture
VGGT	Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security
WaPOR	Water Productivity Open-access Portal
WASAG	Global Framework on Water Scarcity in Agriculture
WEFE	Water–Energy–Food–Ecosystems
WUA	water users' association

Chemical formulae, currencies and units

CO_2eq	carbon dioxide equivalent
ha	hectare
kg	kilogram
Mha	million hectares
N	nitrogen
USD	United States dollar

GLOSSARY

Agricultural land. The total area of land used for crop production and livestock raising. This includes arable land (land used for temporary crops), land under permanent crops (e.g. orchards) and permanent pastures (land used for grazing).

Agrifood systems. The entire range of actors and interlinked activities that add value in agricultural production and related off-farm activities such as food storage, aggregation, post-harvest handling, transportation, processing, distribution, marketing, disposal and consumption.

Agricultural production refers to primary crop, livestock, fisheries and forestry production.

Agroecology. A holistic approach that applies ecological and social concepts to the design and management of sustainable agriculture and food systems. It focuses on optimizing interactions between plants, animals, humans and the environment, aiming for sustainable and equitable food systems.

Agroforestry. A land-use system that deliberately integrates trees and shrubs with agricultural crops and/or livestock on the same land unit. This integration can be spatial, temporal or both, aiming to create more sustainable and diverse land-use systems.

Arable land. Land used for cultivation of temporary crops in rotation with fallow, meadows and pastures within cycles of up to five years. It is the total of areas under temporary crops, temporary meadows and pastures, and temporary fallow.

Area equipped for irrigation. Land area equipped with irrigation infrastructure and equipment that can provide water to crops and which are in working order. The equipment does not have to be used during the reference year. The area equipped for irrigation comprises areas equipped for fully controlled irrigation by any of the methods of surface, sprinkler or localized irrigation. It also includes areas under partially controlled irrigation methods of spate irrigation (controlling floodwaters to water crops), equipped wetlands and inland valley bottoms, and equipped flood recession. It excludes manual watering of plants using buckets, watering cans or other devices.

Attainable yield. In the context of GAEZ, the maximum yield that can be achieved under specific agroecological conditions, combining agroclimatic potential yields with soil and terrain evaluations. It takes account of biophysical limitations such as temperature, moisture availability, soil type and slope, as well as specified levels of agronomic inputs and management practices. Attainable yield is distinct from potential yield as it integrates realistic constraints of soil and terrain, providing a more practical estimate of productivity for a given crop under defined conditions.

Cropland. Land used for the cultivation of crops. It is the total of areas under arable land and permanent crops.

Cropping intensity. The ratio of the sum of the harvested areas to total cropland for a given area, region or country in a year. Cropping intensity is usually expressed as a percentage or ratio. A cropping intensity of 100 percent means that all the cropland has been harvested once during the year. Cropping intensity is above 100 percent when part of the land has been harvested more than once and below 100 percent when part of the cropland has not been harvested (this happens when there is a crop failure).

Ecosystem approach. A strategy for the integrated management of land, water and living resources that promotes conservation and equitable, sustainable use. It is based on the application of appropriate scientific methodologies focused on levels of biological organization that encompass the essential processes, functions and interactions among organisms and their environment. It recognizes that humans, with their cultural diversity, are an integral component of ecosystems.

Governance. The formal and informal rules, organizations and processes through which public and private actors articulate their interests, make decisions and implement them related to food and agriculture.

Harvest area (or harvested area). The total land area from which a crop is gathered or harvested. This definition excludes areas sown or planted where there was no harvest due to factors such as crop failure or damage.

Land. A delineable area of the Earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below this surface, including those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes and swamps), the near-surface sedimentary layers and associated groundwater reserve, the plant and animal populations, the human settlement pattern, and the physical results of past and present human activity such as terracing, water storage and drainage structures, infrastructure, and buildings.

Land cover. The observed physical and biological cover of the Earth's land surface including natural features such as vegetation, soils and waterbodies, as well as human-made features such as buildings and roads. Land cover is distinct from land use, which refers to the activities people undertake on a particular land cover type.

Land degradation. The reduction in the capacity of the land to provide ecosystem goods and services and assure its functions over time due to human action.

Land productivity. The amount of agricultural output produced per unit of land area. It essentially quantifies how efficiently land is being used to produce crops or livestock, and can be measured in terms of value, biomass or other relevant units.

Land suitability. The assessment of how well a given piece of land can support agricultural production for a specific crop, considering factors such as climate, soil and terrain.

Land tenure. Relationship, whether legally or customarily defined, among people – as individuals or groups – with respect to land. It is an institution, with rules invented by society to regulate behaviour. The rules cover from how access is granted to the right to use, control and transfer land, as well as associated responsibilities and restraints.

Land use. The activities, arrangements and inputs that people undertake on a particular land cover type to produce, change or maintain it. Land use encompasses a wide range of human activities, from farming and forestry to urban development and infrastructure, and is a key aspect of land management and sustainable development.

Marginal land. Land with low productivity due to biophysical conditions such as rugged terrain, poor soil quality, extreme weather conditions (including scattered and low precipitations) and other factors, or productive land constrained by socioeconomic factors such as human-induced land degradation, market price instability, land tenure conditions and limited access to markets and infrastructure, which render it incapable of cost-effective production under given conditions.

Opportunity crops are crops with great unrealized potential to improve food and nutrition security in the context of climate change. Most are nutrient-rich traditional and indigenous crops that have suffered historically from underinvestment.[a]

a Herrick, J.E., Fowler, C., Sibanda, L.M., Lal, R. & Nelson, A.M. 2024. The vision for adapted crops and soils: how to prioritize investments to achieve sustainable nutrition for all. *Nature Plants*, 10: 1840–1846. https://doi.org/10.1038/s41477-024-01867-w; Sileshi, G.W., Borgemeister, C., Kuyah, S., Nath, A.J. & Arshad, S. 2025. About neglected and underutilized crops for agroecological transition of food systems. *CABI Agriculture and Bioscience*, 6(1): 0047. https://doi.org/10.1079/ab.2025.0047

Permanent crops. Land cultivated with long-term crops which do not have to be replanted for several years such as cocoa and coffee. It also includes the land under trees and shrubs producing flowers such as roses and jasmine as well as nurseries.

Potential yield. The highest crop yield achievable under specific agroclimatic, soil and terrain conditions, considering specific management assumptions and agronomic input levels.

Representative Concentration Pathway (RCP). A scenario that models future greenhouse gas concentrations and their impact on climate. They provide a framework for understanding how different levels of greenhouse gas emissions might affect the Earth's climate system by the year 2100 and beyond. RCPs have been formally adopted by the Intergovernmental Panel on Climate Change (IPCC).

Shared Socioeconomic Pathway (SSP). A scenario that models future societal development and its impact on greenhouse gas emissions.

Water productivity. In agriculture, the amount of agricultural output produced per unit volume of water applied or consumed in production. It essentially quantifies how efficiently water is being used to produce crops or livestock, and can be measured in terms of value, biomass or other relevant units.

Water scarcity. An imbalance between supply and demand of freshwater in a specified domain (e.g. a country, region, catchment or river basin) as a result of a high rate of demand compared with available supply, under prevailing institutional arrangements (including price) and infrastructural conditions. Symptoms are unsatisfied demand, tensions between users, competition for water, overextraction of groundwater and insufficient flows to the natural environment.

Water stress. The proportion of total freshwater withdrawn by all sectors (agriculture, industry and municipal) compared with the total renewable freshwater resources, after accounting for environmental flow requirements. This ratio, often expressed as a percentage, indicates the pressure on a country's freshwater resources.

Water tenure. The relationships, whether legally or customarily defined, between people (individuals or groups) and water resources. It encompasses the rights to access, use, manage and participate in decisions related to water resources.

Water-use efficiency (water efficiency). The ratio formed when dividing the amount of water consumed in a specific use by the amount of water allocated or delivered to that use.

Wildfire. Any unplanned and uncontrolled vegetation fire that, regardless of ignition source, may negatively affect social, economic or environmental values and require suppression response or other action according to agency policy.

Yield gap. The difference between crop yield obtained in a given area and attainable yield.

CORE MESSAGES

Challenges for land and water resources

➔ Land, soil and water form the foundations of agricultural production. Agricultural production and productivity were able to keep up with the increasing needs of a rapidly growing population in the past, but this was achieved at a substantial environmental and social cost.

➔ Human-induced land degradation affects cropland, pastures and forested land on which people depend for their livelihoods. Intensive agricultural practices and unsustainable use of chemicals increasingly lead to pollution and the depletion of land, soil and water resources.

Status and trends in the management of land and water resources

➔ During the 60-year period between 1964 and 2023, most of the increase in agricultural production was achieved through intensification, while the expansion of agricultural land was limited to just 8 percent.

➔ More than 1 660 Mha of land, corresponding to more than 10 percent of the world's land area, have been degraded by unsustainable land-use and management practices, with more than 60 percent of this degradation occurring on agricultural lands (including cropland and pastureland).

➔ Future agricultural development pathways need to be based on the transformation of agrifood systems for better production, better nutrition, a better environment and a better life, leaving no one behind. The additional production required to satisfy the future increase in demand must be realized through more efficient, inclusive, resilient and sustainable production systems that address the socioeconomic and environmental dimensions of sustainable development.

Producing more and better: the potential

➔ The potential exists to feed the 9.7 billion people predicted to make up the world's population by 2050, and the approximately 10.3 billion people when the global population is projected to peak around 2085. The conditions under which this food production takes place will determine the associated environmental, social and economic costs. However, the potential for agricultural expansion is limited, as further land conversion to cropland would have impacts on other ecosystems and their services, including forests, grasslands and wetlands.

➔ There is scope for significant increases in land productivity in most developing regions and for most types of crops. The bulk of increased food production should come from reductions in yield gap, the selection of crops suitable for agroecological conditions, and the adoption of sustainable management practices adapted to each crop.

➔ Climate change affects land suitability for many crops, with suitable areas for given crops usually moving to higher latitudes and altitudes. For some crops, agricultural water demand will increase in future climate scenarios, while the available water resources become more variable and less reliable.

➔ In areas where land and water resources are scarce, satisfying competing societal objectives (agriculture, industry, urbanization, energy, biodiversity conservation) often implies trade-offs and difficult choices in resource allocation. Integrated land and water resource planning provides tools to manage the competition for resources and optimize resource use.

Sustainable land and water resources management: technical solutions

➔ Multiple technical solutions exist to achieve sustainable land, soil and water management. They depend on the socioecological context and production system, of which there are a wide variety around the world. An appropriate enabling environment is required for the successful adoption of solutions by land and water users.

➔ The productivity of rainfed agriculture can be improved through a more systematic adoption of conservation agriculture and the use of drought-tolerant crop varieties and drought-resilient practices such as soil moisture conservation, crop diversification and organic composting. These practices have the potential to make a significant contribution to the food security of millions of smallholder producers and to enhance soil health and on-farm biodiversity.

➔ Integrating sectoral solutions offers a unified model for sustainable land, water, forest and aquatic resource management that addresses multiple aspects of food security, climate resilience and environmental sustainability. Agroforestry, rotational grazing and forage improvement, and rice–fish farming are just a few examples of such integrated approaches. Together, these technologies and practices create a framework where sustainable resource use is tailored to specific landscapes and enhances resilience to climate change.

An enabling environment for sustainable solutions

➔ Integrated land-use planning, integrated landscape management, integrated water resources management, the Water–Energy–Food–Ecosystems nexus, agroecology, and the agrifood systems approach are essential sustainable and integrated approaches to address the climate, land, soil, water and biodiversity crises, while recognizing that there is no one-size-fits-all solution.

➔ In order for such integrated land, soil and water resources management solutions to be implemented coherently at scale, the following enablers will need to be set in place: policy coherence across sectors; governance of natural resources; data, information and technology; risk management systems including early warning and adaptation and resilience strategies; sustainable financing and investment; innovation; and institutionalized capacity development.

EXECUTIVE SUMMARY

In order to meet the demands of a growing global population, agriculture needs to produce about 50 percent more food, feed and fibre by 2050 compared with the volumes it generated in 2012, according to estimates by the Food and Agriculture Organization of the United Nations (FAO). Achieving such objectives will place additional pressure on the world's already overstretched water, land and soil resources. In an increasing number of regions, food security and agrifood systems are at risk from unsustainable natural resource management practices, urban expansion, higher demand for food, water, energy and biomaterials, and persisting social and gender inequalities in access to and governance of resources.

FAO estimates that more than 1.6 billion hectares (ha) of land, corresponding to more than 10 percent of the world's land area, have been degraded by unsustainable land-use and management practices. More than 60 percent of this degradation occurs on agricultural lands (including cropland and pastureland), creating unprecedented pressure on the world's agrifood systems. Globally, urban areas more than doubled in size in just two decades, growing from 33 million hectares (Mha) in 1992 to 71 Mha in 2015. This expansion consumed 24 Mha of some of the most fertile croplands, 3.3 Mha of forestlands and 4.6 Mha of shrubland.

Climate change is exerting additional stress on land and water resources, exacerbating existing risks to livelihoods, biodiversity and agrifood systems. This trend is predicted to continue due to the increased demand for food and other products, land degradation, climate change and biodiversity loss. With consequences for all components of agrifood systems, including land, soil and water resources, the impacts of climate change are increasingly evident in the form of rising temperatures, changing precipitation patterns, and mounting incidence of extreme events such as droughts and floods. The growing frequency and intensity of disasters caused by extreme weather events are taking an unparalleled toll on food production, with annual losses estimated at USD 123 billion, equivalent to 5 percent of global agricultural gross domestic product. This bleak picture is aggravated by an alarming rise in social instability and conflicts in many countries and regions, which affected an estimated 1.9 billion ha or nearly 40 percent of agricultural land in 2023.

Despite the scale of the challenges facing the Earth's natural resources, agriculture – if managed and practiced in a sustainable manner – has the potential to meet the needs of the world's growing population, which is projected to increase to 9.7 billion by 2050 and to peak at 10.3 billion by 2085. Sustainable agricultural practices can lead to direct improvements in the state of land, soil and water resources and generate valuable ecosystem benefits. In parallel, sustainable management of land, soil and water resources can make a significant contribution in terms of both mitigation of and adaptation to climate change.

Any strategy aimed at achieving sustainable agricultural production and management of land and water resources requires a profound shift in the way that such critical resources are managed, underpinned by accurate information and finance, and accompanied by synergistic efforts and initiatives from beyond the domain of natural resource management. In the specific and critical sphere of climate change, the currently inadequate levels of investment and climate finance need to be stepped up. It is also important to keep in mind that any measures aimed at climate mitigation and adaptation must be carefully planned to avoid maladaptation or unintended consequences, including additional pressure on scarce water resources or further degradation of land and soil resources.

This third edition of *The State of the World's Land and Water Resources for Food and Agriculture* – for the first time part of FAO's flagship State of the World series of publications – focuses on the potential for improving food, feed and fibre production, examining how to produce more and better to meet the needs of a growing population, and how best to manage the Earth's land, soil and water resources to achieve that aim.

Taking a wide-ranging and detailed look at land, soil and water – which form the foundation of agricultural production – the report considers crops, rangeland, forests, fisheries and aquaculture. There is a special focus on the scope for improved production of the main cultivated crops, now and under future climate scenarios, through a thorough analysis of data derived from the latest Global Agro-Ecological Zoning (GAEZ) assessment co-led by FAO and the International Institute for Applied Systems Analysis. The report leverages key data and knowledge to support and inform policymaking at all levels. Furthermore, it explores options for the sustainable use and management of land, soil and water resources, with the aim of narrowing the yield gap of main crops and thereby increasing agricultural production. It proposes actions and solutions illustrated by examples, and identifies the enablers that would be required to scale up such actions and solutions for sustained impact. The overall goal of the report is to analyse and promote opportunities for agrifood systems transformation through the sustainable use and management of land, soil and water resources, so that these three critical components of agrifood systems can become more resilient and more productive now and in the future.

HUMAN-INDUCED NATURAL RESOURCE DEGRADATION

In recent decades, advances in agricultural production and productivity have made it possible to keep pace with increasing demand from a rapidly growing population, but this progress has exacted a high price in environmental and social terms. The substantial increases in land productivity required to feed, clothe, shelter and generate livelihoods for growing numbers of people have had an often deleterious impact on biodiversity, other ecosystem functions and services, and on the quality and quantity of land and water resources. Human-induced land degradation has negatively affected cropland, pastures and forested land, jeopardizing the ability to produce food, fuel and fibre for the generations to come. Intensive agricultural practices and excessive use of chemicals have increasingly led to pollution and the depletion of land, soil and water resources.

Extending over 4.8 billion ha – the equivalent of one-third of the Earth's land surface – agriculture has a greater impact on land and water resources compared with any other economic sector. In an increasingly vicious circle, unprecedented pressure on land, soil and water resources has seriously compromised the performance and future prospects of agriculture itself, resulting in further loss of productive land and reduced water availability for farming and other forms of agricultural production. Agricultural expansion drives deforestation and is one of the primary causes of the degradation of carbon-rich ecosystems such as peatlands. An estimated 64 percent of agricultural land is at risk of pesticide pollution, which damages biodiversity by destroying pollinators, harms soil microbiota and makes agrifood systems less resilient to pests, pathogens and climate change.

Accounting for 72 percent of global freshwater withdrawals – a figure predicted to rise further in the future – agriculture contributes to and is increasingly affected by water scarcity. Overexploitation of groundwater and seawater intrusion in coastal aquifers is widespread, with major implications for food security.

THE HIGH COST OF FEEDING A GROWING POPULATION

Between 1964 and 2023, most of the increases in agricultural production recorded worldwide were the result of intensification, with expansion of agricultural land limited to 8 percent. A case in point was cereal production, which underwent a global increase of 213 percent over this 60-year period; this was mostly due to higher yields and it compares with an increase in harvested area of just 10 percent.

During these six decades, the intensification that generated this significant upturn in agricultural production was achieved through improved crop varieties, seeds and agronomic practices, better access to water, and more systematic use of fertilizers. The world's total irrigated land area more than doubled during this period and by 2023, 23 percent of all croplands were equipped for irrigation. Irrigated croplands produce 48 percent of all crops in value terms, indicating that irrigated land is 3.2 times more productive than rainfed land in value terms. On average, the yield of irrigated land is 76 percent higher than that of rainfed land.

Global average use of fertilizer in 2023 was 116 kg per hectare of cropland, more than four times greater than in 1964. Areas planted with permanent crops, including oil palm, coffee, tea and other tree crops – mostly cultivated for global markets – increased by 42 percent or 56 Mha between 2001 and 2023 in nearly all regions and subregions of the world.

The degree of agricultural intensification contributed to limiting the need for further expansion of agricultural land – and the subsequent encroachment on other lands – to achieve the required levels of increased output. In some parts of the world, the intensification strategy even resulted in a reduction in agricultural land. Central and Northern America and Southern Europe recorded a net reduction in arable land between 2001 and 2023.

However, despite the benefits in terms of output, the increase in agricultural production, whether through expansion or intensification, came at a high environmental cost, contributing to a substantial share of greenhouse gas emissions and biodiversity loss, degrading land and inland water ecosystems, polluting soils and aquifers, and pushing water withdrawal beyond sustainability limits in an increasing number of regions. Unsustainable farming and management practices have led to the degradation of 996 Mha of agricultural lands; this accounts for over 60 percent of human-induced land degradation, which affects a total area of more than 1 660 Mha. Currently, an estimated 1.2 billion people, or about one-sixth of the global population, live in agricultural areas with severe water constraints.

In order to achieve the much-needed increase in agricultural production, without unleashing the negative side effects that will inevitably compromise any such gains and their long-term prospects, future agricultural development models need to be radically overhauled. The additional production required to meet the increased needs has to be achieved in a much more sustainable manner, from both a biophysical and a socioeconomic perspective. More efficient use of land and water resources is an essential prerequisite of any such paradigm, ensuring that water withdrawal – whether from surface water or groundwater – takes place within the limits of sustainability, and that decisions on land use are based on the potential to produce food sustainably.

UNLOCKING THE POTENTIAL TO PRODUCE MORE AND BETTER

If land and water resources are managed carefully, the potential exists to produce enough food for the 9.7 billion people predicted to make up the world's population by 2050, and the approximately 10.3 billion people expected when the global population is projected to peak around 2085. This means that cropland would need to increase from its current 1.6 billion ha to 1.9 billion ha in 2050 and 2.1 billion ha in the mid-2080s, which is significantly less than the 4 billion ha of prime and good land currently available. However, such global calculations do not factor in the substantial variations between regions and countries, nor the competition with other uses and the degradation of currently used land. In reality, the potential for agricultural expansion is very limited. This is because further land conversion to cropland would impact other ecosystems, including forests, grasslands and wetlands. Preserving these ecosystems is crucial to addressing the challenges of climate change and dwindling biological diversity. Holistic approaches such as integrated land-use planning (ILUP) are required to optimize the use of available suitable land for food production, while managing competition across different land uses and other economic sectors.

In addition, the conditions under which any increased production is accomplished will be pivotal in determining any environmental, social and economic impacts that may ensue. Any increase in cropland will be at the expense of other land uses and will further increase agriculture's own very considerable environmental footprint. It is therefore essential to evaluate the repercussions and trade-offs in terms of further degradation, especially of biodiversity and ecosystems' regulating functions. At a more local level, in areas where land and water resources are scarce, integrated land and water resource planning offers scope for managing the competition between different sectors for resources and optimizing resource use.

Decision-making about extending crop cultivation must take geographical and biophysical factors into account. Regions such as Africa and South America have scope for further expansion, while Asia has broadly reached its limit. In addition, while agricultural production is mostly practiced on prime or good agricultural land, in some areas producers are obliged to work on marginal land. Despite the constraints, there is potential for increasing production and productivity on marginal lands, using sustainable management practices and techniques, while also addressing and eliminating the root causes and drivers of land degradation. Such practices must be adapted to local conditions and need to be supported by appropriate financial and policy instruments.

The alternative to cropland expansion as a strategy for increased agricultural production is intensification – increasing production on existing agricultural land. The yield gap analysis highlights the potential for increasing the production of current agricultural lands, now and in the future. This approach is critical to producing enough food for the projected rise in the global population, but it is also vital to pursue intensification in a far more sustainable manner compared with the past. In most developing regions, there is potential to achieve substantial increases in land productivity for most types of crops, using a three-pronged approach based on reducing the yield gap, selecting crops that are suitable for agroecological conditions (e.g. opportunity crops) and adopting sustainable management practices adapted to each crop.

NARROWING THE YIELD GAP

Yield gap refers to the difference between current yield and attainable yield – a calculation that reveals opportunities for improvement in many regions where crop yields are lower than the potential yield under optimum management. A clear example is sub-Saharan Africa, where the yield of rainfed crops is only 24 percent of the potential yield under appropriate management practices. In order to identify areas where an increase in food production is achievable, the report analyses the scope for narrowing the yield gap for selected crop groups and crops in different regions under different management conditions following the GAEZ methodology and using the latest available GAEZ assessment. The GAEZ methodology matches available global georeferenced datasets on agroclimatic, soil and terrain conditions with specific crop requirements to determine suitable agricultural land-use options and model the agronomically attainable yield for 52 crops. These factors are used to evaluate the suitability of land and the production potential of individual crops under various input and management conditions, estimate yield gaps by comparing current yield with attainable yield, and identify hotspots where more productive land use is possible.

Irrigation addresses a key constraint to cropland suitability and increased production by ensuring adequate and regular soil moisture for crops.

However, its use can have negative consequences and it is important that careful assessments and planning are conducted at farm, river basin and aquifer levels to ensure sustainability. Introducing better agricultural practices, including improving nutrient-use efficiency and fertilizer application, integrating organic inputs and using sustainable mechanization, can help to combat soil depletion, which is a major limiting factor for production levels in many areas. Also important are the adoption of suitable crop varieties and the promotion of agrobiodiversity, including the cultivation of opportunity crops adapted to specific conditions and cultures.

Given the significant impact of climate change on agriculture, and the prospects of its influence on land suitability for many crops in the future, this edition of the report makes a detailed analysis of how changes in temperature, precipitation and other factors are likely to affect land suitability. Using GAEZ data and applying Intergovernmental Panel on Climate Change climate scenarios, the report assesses the impact of climate change on land suitability, crop water demand and crop production potential for selected crop groups. The findings show that climate change is likely to alter the distribution of suitable areas for the crops analysed under rainfed conditions, with projected outcomes depending on the climate model applied. For some crops, agricultural water demand will increase under future climate scenarios, while the available water resources become more variable and less reliable.

A ROADMAP FOR BALANCING INCREASED FOOD PRODUCTION WITH ECOSYSTEM HEALTH

Given the interconnected nature of land, water, forest and aquatic resources, their sustainable management depends on a holistic approach that blends complementary technical solutions, generating overall benefits that are greater than the sum of their parts. Examining some of the multiple technologies and approaches available to achieve sustainable land, soil and water management, the report outlines a roadmap for decision-makers seeking to balance improved food production with ecosystem health. The roadmap underscores how integrated management practices are essential to building efficient, inclusive, resilient and sustainable agrifood systems.

Together, the complementary strategies presented – each of which is context-specific and dependent on the appropriate enabling environment – address challenges caused by water scarcity, soil and land degradation, deforestation and biodiversity loss. Integrating sectoral solutions offers a unified model for sustainable land, water, forest and aquatic resource management that addresses multiple aspects of food security, climate resilience and environmental sustainability. To cite just a few examples of such approaches, integrated plant production and forestry enhance soil health and restore degraded landscapes, both of which are essential to ensure long-term land productivity and adaptation to climate change. In rainfed agriculture, a focus on organic amendments, crop diversification and conservation tillage directly supports forest restoration by fostering soil conditions that stabilize and enrich surrounding landscapes. Agroforestry systems, known for their resilience and high biodiversity, complement these practices by providing long-term soil benefits, such as increased soil moisture retention and carbon sequestration. Integrating agroforestry practices within pasturelands can provide shade, improve forage quality and enhance soil health, while rotational grazing maintains productive grasslands that prevent soil erosion and loss of biodiversity. By encouraging the strategic inclusion of trees in grasslands, these complementary practices promote resilience to climate extremes, help to manage erosion and enhance carbon sequestration within pasture ecosystems.

For water resources – a critical factor in any strategy for increased agricultural production – there is a strong case for adopting a joint management approach to support both agriculture and fisheries, maximizing food production while conserving water. Designing and managing water for multiple uses (e.g. agriculture, drinking water, industries, livestock and fisheries) can raise the social and economic productivity of water in water management systems. Multifunctional farm ponds can store water for irrigation and domestic purposes and simultaneously be used to raise fish as a source of food and revenue for local communities. Integrating agriculture with aquaculture provides a means of recycling water and nutrients and increasing income. Rice–fish farming systems are a prime example of how this synergistic approach can contribute to both household nutrition and finances, while simultaneously using water more efficiently.

Enhancing the productivity of water in irrigation can be achieved through modernization, including fish-friendly irrigation infrastructures that can enhance both aquatic biodiversity and food security without compromising agricultural productivity. For the long-term success of modernized irrigation systems, a benchmarking approach that encompasses technical, institutional, socioeconomic and environmental factors is essential.

Combining improved water management and grazing practices – by selecting drought-tolerant and water-efficient pasture species (including grasses and woody species), integrating forage and legumes in pastures, and introducing precision livestock farming technologies – can make a significant contribution to better land and water management for pasture and feed production.

Regarding food production for the world's increasingly city-based populations, the report examines the potential of urban and peri-urban agriculture, with a focus on hydroponics, and vertical and rooftop farming – techniques that have proved to be effective around the world. In addition to sustainable and integrated practices on site, other innovative tools such as early warning systems and climate forecasting play an increasingly important role in supporting agricultural production in all its forms.

In every sector and setting, the adoption of technical solutions requires community engagement, data-driven solutions and adaptive practices that consider both the environmental and the social dimensions of resource management. Provided that all these prerequisites can be put in place, the complementary strategies outlined here have strong scope for transforming agrifood systems in line with FAO's overall objective of achieving better production, better nutrition, a better environment and a better life, leaving no one behind.

AN ENABLING ENVIRONMENT FOR BETTER LAND, SOIL AND WATER RESOURCES MANAGEMENT

Ensuring an enabling environment is the final – but critical – piece in the puzzle designed to scale up sustainable land, soil and water resources management, through effective and conducive legal, policy and organizational frameworks. First and foremost, sustainable and integrated solutions are required to address food, climate, land, soil, water and biodiversity crises. The need for such solutions has gained recognition in recent years through various international processes, calls for action, targets and commitments.

Integrated land-use planning, integrated landscape management, integrated water resources management (IWRM), the Water–Energy–Food–Ecosystems (WEFE) nexus, agroecology and the agrifood systems approach are essential sustainable and integrated approaches to address these challenges.

An evidence-based integrated planning process is essential to incorporate the needs and views of different sectors and stakeholders, considering emerging opportunities to enhance production in a sustainable manner and avert planning decisions that could have unintended or unjust consequences. Integrated land-use planning is one such approach, and its benefits are examined in this report, in terms of addressing challenges and competing demands. Modern approaches to ILUP are based on the principles of decentralization and participation, acknowledging that farmers, herders, fisherfolk and forest dwellers have a legitimate stake in the planning process, together with actors who may have separate and at times competing interests in the use of land and water resources, such as for housing, energy, industry, mineral extraction, recreation or tourism.

In tandem and in close cooperation with ILUP, IWRM is advocated as a tool for optimizing the spatial and temporal allocation of water resources for different needs and among different users. Institutional arrangements at local, national, regional and international levels are essential to manage trade-offs and conflicting demands, especially given the agriculture sector's massive consumption levels of global freshwater resources.

Among the various models discussed in *The State of the World's Land and Water Resources for Food and Agriculture 2025*, the WEFE nexus is highlighted for its potential to improve resilience, maximize synergies, promote the participation of stakeholders, and enhance the sustainability of agrifood systems. Adopting the WEFE nexus approach acknowledges the interconnectedness between water, energy and agrifood systems and their impact on ecosystems. For example, water is essential for the production of energy such as hydropower and the cooling of coal-fired or nuclear power stations; energy is critical for accessing and distributing water; and both water and energy are important in agrifood systems, from production, transformation and marketing through to consumption. Agrifood systems also have an impact on both water and energy, so taking account of and planning for their different interactions is essential.

In order for such integrated land, soil and water resources management solutions to be implemented coherently at scale, the following seven enablers must be set in place: i) policy coherence across sectors; ii) governance of natural resources; iii) data, information and technology; iv) risk management systems including early warning and adaptation and resilience strategies; v) sustainable financing and investment; vi) innovation; and vii) institutionalized capacity development.

Better coherence between sectoral policies is needed to maximize the gains associated with land and water management and address overlaps and trade-offs between conflicting objectives. This requires adapting and strengthening institutions and regulatory environments.

Stronger policies to promote sustainable land, soil and water management should include clear land and water rights, incentives for sustainable practices, and disincentives for unsustainable ones. Regulatory frameworks can create a more conducive environment for public and private sector investments. Securing access to resources for smallholders and vulnerable groups offers the potential to enhance productivity, protect resources and contribute to inclusive rural development.

Data and information are key to ensuring the sustainable and productive management of land and water. The rapid development of information and communication technologies, including remote sensing, offers new opportunities for support to land and water management. Efforts should be made to ensure that the right type of information reaches the different decision-makers at all levels.

Understanding and addressing interconnected, systemic risks and their underlying drivers is essential for building resilient and sustainable agrifood systems that can support long-term food security and nutrition and human well-being for a growing population. Tackling these complex, overlapping challenges requires integrated, cross-sectoral solutions aligned with the objectives of the three Rio Conventions, and incorporating disaster risk reduction strategies alongside humanitarian policies to ensure that no one is left behind.

Public and private investment instruments that increase agricultural productivity, contribute to inclusive development and preserve natural resources need to be developed and put into practice. Sustainable investments require coordinated collaboration between the public sector and the financial and private sectors.

Farmers, especially in developing regions, often lack access to the necessary technologies, information and skills required to implement sustainable practices, which hinders the adoption of innovative and sustainable land and water management techniques. Farmer-centred training programmes should use modern communication technologies to promote the adoption of sustainable practices that strengthen resilience while ensuring the overall improvement of farmers' socioeconomic status.

In areas where land and water resources are scarce, satisfying competing societal objectives (agriculture, industry, urban development, energy, biodiversity conservation) often implies trade-offs and difficult choices in resource allocation. Integrated land and water resource planning provides tools to manage the competition for resources and optimize resource use.

The need for integrated solutions to address food, climate, land, soil, water and biodiversity challenges is emerging from several international processes. The three so-called Rio conventions – the Convention on Biological Diversity, the United Nations Convention to Combat Desertification and the United Nations Framework Convention on Climate Change – were among the first instruments to recognize the inextricably linked nature of the challenges facing the planet and humanity and to highlight the role of agrifood systems in tackling the interconnected triple challenges. They offer a framework for countries to enhance their efforts towards addressing these intertwined objectives in an integrated manner.

PLURINATIONAL STATE OF BOLIVIA
A farmer scatters seeds on a dry ploughed field on the Altiplano.
© Matteo Sala

CHAPTER 1
CHALLENGES FOR LAND AND WATER RESOURCES

KEY MESSAGES

➔ Land, soil and water form the foundations of agricultural production. Progress in agricultural production and productivity has made it possible to keep up with increasing demand from a rapidly growing population, but this has been achieved at a substantial environmental and social cost.

➔ Land productivity has increased substantially to respond to increasing demand. However, this has often had a negative effect on the environment, in particular on biodiversity, other ecosystem functions and services, and the quality and quantity of land and water resources.

➔ Human-induced land degradation affects cropland, pastures and forested land and the people depending on land for their livelihoods. Intensive agricultural practices and unsustainable use of chemicals increasingly lead to pollution and the depletion of land, soil and water resources.

➔ Unprecedented pressure on land, soil and water resources and competition between sectors are increasingly affecting agriculture, resulting in loss of productive land and reduced water availability for agriculture. As the main sector for freshwater withdrawals, agriculture contributes to and is increasingly affected by water scarcity. Overexploitation of groundwater and seawater intrusion in coastal aquifers are widespread.

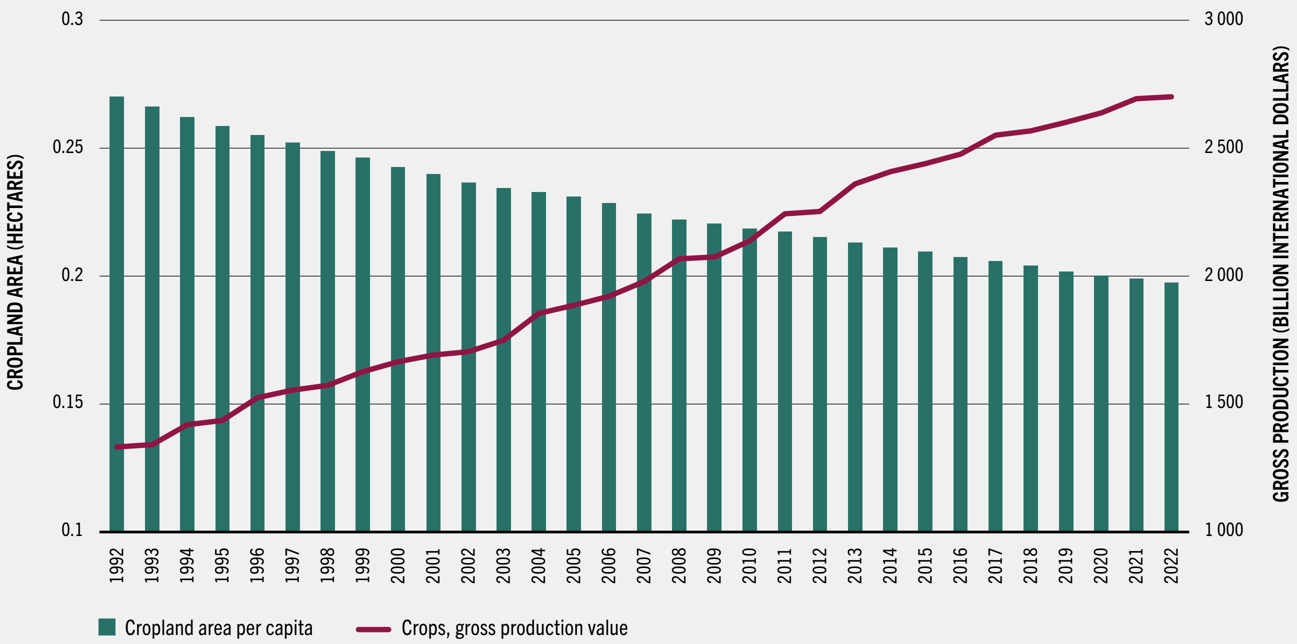
➔ Social and gender inequalities persist in access to and governance and control of land and water resources, and undermine food security, especially for the most vulnerable groups.

➔ Climate change affects all components of agrifood systems, including land, soil and water resources, with impacts already observed in many areas, including the increasing occurrence of extreme events such as droughts and floods. In some areas, climate change exacerbates already problematic water scarcity.

➔ Sustainable management of land, soil and water resources can play a key role in both mitigation of and adaptation to climate change. However, investments and climate finance continue to be scarce and inadequate.

➔ Further, climate mitigation and adaptation measures need to be carefully planned to avoid maladaptation or unintended consequences, including additional pressure on scarce water resources or further degradation of land resources.

FIGURE 1 GLOBAL TRENDS IN CROPLAND AREA PER CAPITA AND GROSS PRODUCTION VALUE OF CROPS, 1992–2022



SOURCES: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land Use. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0; FAO. 2025. FAOSTAT: Value of Agricultural Production. https://www.fao.org/faostat/en/#data/QV. [Accessed on 13 February 2025]. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig01

According to estimates by the Food and Agriculture Organization of the United Nations (FAO), on average, global agriculture needs to produce about 50 percent more food, feed and fibre by 2050 compared with 2012 (FAO, 2017, 2022a), with important differences between regions. In 2022, the global value of crop production reached 2.7 trillion international dollars,[b] nearly double its value in 1992. During the same period, per capita cropland area decreased by 27 percent globally, from 0.27 hectares (ha) in 1992 to less than 0.2 ha in 2022. In contrast, a progressive increase in land productivity was observed over the same period (see Figure 1).

However, in an increasing number of regions, food security and the agrifood systems on which it is based are at risk from unsustainable natural resource management practices, urban expansion, higher demand for food, water, energy and biomaterials, and persisting social and gender inequalities in access to and governance and control of resources (FAO, 2022a). Climate change is increasingly affecting food security through higher air temperatures, changing precipitation patterns and greater frequency of extreme events – all factors that affect food production. This trend is projected to create additional stress on land and water resources, exacerbating existing risks to livelihoods, biodiversity and food systems. (IPCC, 2019, 2023).

b FAO uses "international dollars", derived using a Geary-Khamis formula for the agriculture sector. This method assigns a single "price" to each commodity (FAO, 2005). Values are in constant 2014–2016 international dollars. International dollars avoid the use of exchange rates for obtaining continental and world aggregates. One international dollar would buy in any cited country a comparable amount of goods and services that USD 1 would buy in the United States of America (World Bank, 2025).

Lately, such land-use challenges have been aggravated by an increase in social instability and conflicts in many countries and regions of the world, affecting an estimated 1.9 billion ha or nearly 40 percent of agricultural land in 2023 (Raleigh, Kishi and Linke, 2023).

This chapter reviews some of the challenges that most directly affect the productive and sustainable management of land, soil and water resources for food and agriculture. ■

HUMAN-INDUCED LAND DEGRADATION AND DEFORESTATION

The United Nations Convention to Combat Desertification (UNCCD) estimates that 52 percent of global agricultural land is degraded (UNCCD, 2022a). According to FAO, unsustainable land-use management and practices affect 1 660 million ha (Mha) of land globally (FAO, 2022a). Conservative estimates of the impact of soil erosion and salinization indicate that 82 Mha of rainfed cropland and 24 Mha of irrigated cropland are degraded from salinization processes alone (FAO, 2024a). Importantly, land degradation leads to a loss of habitat and a decline in species diversity, negatively impacting ecosystems and their ability to provide essential services and making them more vulnerable to drought (Rackelmann *et al*., 2024).

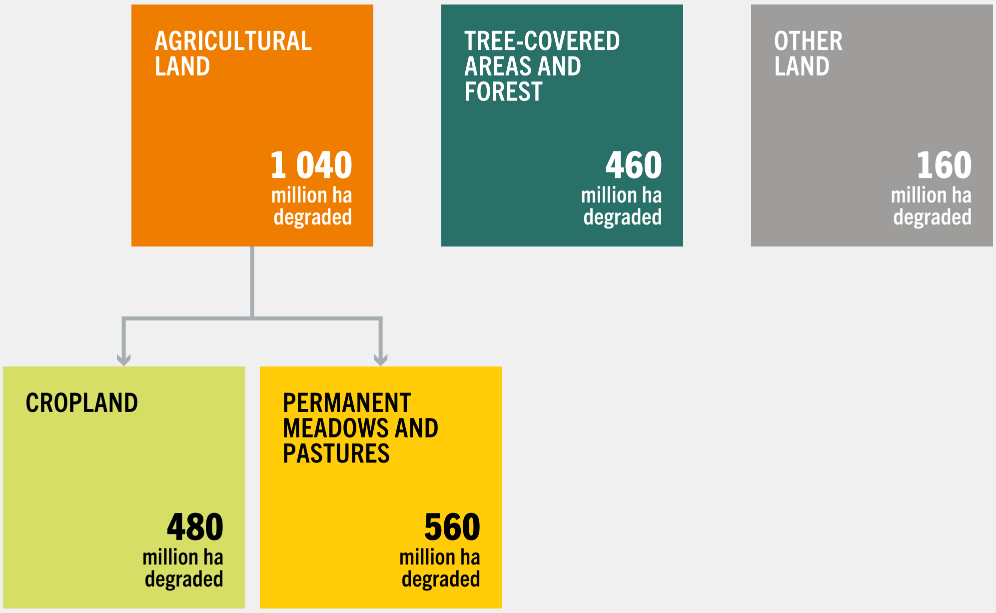
Land degradation increases flood and drought hazards. These events are not just caused by the excess or deficit of precipitation. They also depend on how the land surface receives, stores, transmits and releases water. When soils are healthy, porous, well graded, and rich in organic matter and biodiversity, they can readily absorb excess precipitation, attenuate peak flows and recharge the root-zone storage. Conversely, soils damaged by erosion, compaction, crusting or the exposure of dense clay layers can see their infiltration capacities reduced by 90 percent or more. Under such conditions, even moderate storms can cause flash floods, while dry spells can translate into agricultural droughts since the degraded root-zone storage cannot hold the required moisture to sustain crops until the next precipitation event. Seo *et al*. (2025) noted that regions experiencing the most severe soil structure loss from intensive cultivation, deforestation or overgrazing exhibit the steepest decline in root-zone moisture and the highest flood peaks for comparable rainfall events. This dual impact of flood amplification and drought intensification is largely attributed to degraded land.

Some 480 Mha of human-induced land degradation occur in croplands where nutrient depletion, loss of soil organic carbon and biodiversity, soil erosion and high concentrations of salts constitute the main symptoms of land degradation (Ziadat *et al*., 2025). Around 560 Mha of human-induced degraded land are estimated to be in pastures and land used for animal husbandry, where the degradation is driven by unsustainable grazing practices and the invasion of alien species. In other words, more than 60 percent of human-induced land degradation is occurring in agricultural land (croplands and pasturelands), creating unprecedented pressure on the world's agricultural systems.

Agricultural expansion drives nearly 90 percent of global deforestation (FAO, 2022b) and is a primary cause of the degradation of carbon-rich ecosystems such as peatlands (UNEP, 2022). The practice of burning vegetation for land clearance to sow crops is also one of the main triggers of degradation, as it contributes to loss of soil biodiversity and soil organic carbon and can affect the physical properties of soil such as aggregate stability, water repellency and retention capacity, increasing erodibility (Agbeshie *et al*., 2022).

Human-induced land degradation also affects the 460 Mha of global surface area that are covered with trees, including forests (see Figure 2). Forest fires, although a natural process, are becoming more frequent, aggressive and widespread across the globe due to human activities, and land-use and management practices, as well as climate change. Every year, an estimated 340 to 370 Mha of the Earth's land surface are affected by fire (Giglio *et al*., 2010), including approximately 67 Mha of forested areas (van Lierop *et al*., 2015). There has been an increasing trend in global burnt area since 2021, with a peak recorded in

FIGURE 2 **HUMAN-INDUCED LAND DEGRADATION, 2020**



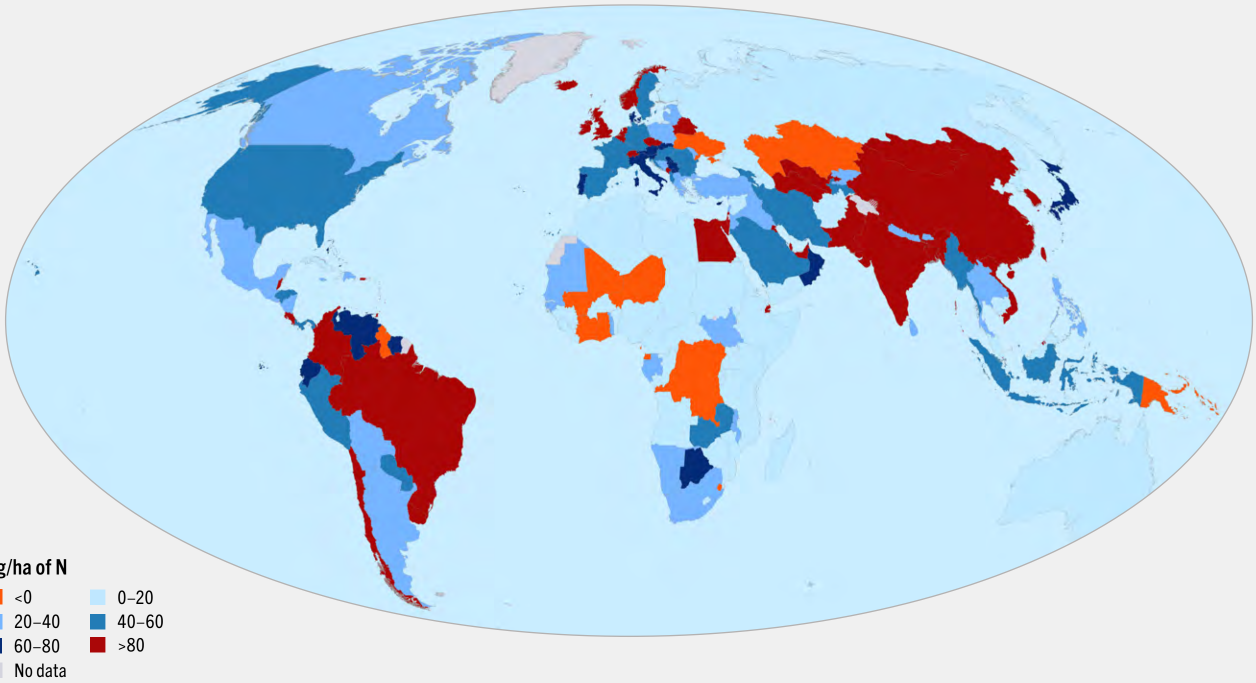
SOURCES: Authors' own elaboration based on FAO. 2022. *The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point*. Rome. https://doi.org/10.4060/cb9910en; Ziadat, F., Conchedda, G., Haddad, F., Njeru, J., Brès, A., Dawelbait, M. & Li, L. 2025. Desertification and Agrifood Systems: Restoration of Degraded Agricultural Lands in the Arab Region. *Agriculture*, 15: 1249. https://doi.org/10.3390/agriculture15121249

2023 (JRC, 2018). Forest fires and wildfires not only cause a loss of above ground biodiversity, but also alter soil biodiversity and functioning (Barreiro and Díaz-Raviña, 2021), contribute to the rapid evaporation of water, and increase the risk of erosion in affected areas (Doerr, Santín and Mataix-Solera, 2023). When wildfires affect carbon-rich soils and peatlands, massive greenhouse gas (GHG) emissions occur. It is estimated that the draining and burning of peatlands to make way for agricultural activities is responsible for nearly 1 gigatonne of carbon dioxide equivalent (CO_2eq) every year or about 6 percent of the carbon emissions from global agrifood systems (FAO, 2023a).

Nutrient imbalances, including negative balances and overloads, contribute to cropland degradation (FAO, 2024b; Figure 3). A positive balance indicates excess application of nitrogen compared with the part that is extracted from the soil by crops (overload). Excessive use of nitrogen fertilizers in most regions leads to soil and water pollution. Conversely, a negative balance indicates a situation where crops extract more nutrients from the ground than those contributed by fertilizers. Soil nutrient depletion is aggravated by removals of crop residues or their burning, a practice widely adopted across the world (Lin and Begho, 2022). In 2022, the overall agricultural use of chemical fertilizers was 35 percent higher than in 2001, but declining rates have been observed since 2020 (FAO, 2025a). Rising prices, market constraints and geopolitical conflicts contribute to limiting the availability of fertilizers to farmers, leading to additional nutrient mining in already depleted soils (Smith *et al.*, 2024).

The inappropriate use of pesticides poses a serious threat to food safety and contributes to the decline in biodiversity by harming soil microbiota, causing the loss of pollinators and making agrifood systems less resilient to pests, pathogens and climate change (FAO, 2019, 2022c).

FIGURE 3 NITROGEN NUTRIENT BALANCES PER UNIT AREA OF CROPLAND, 2022



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 Sudan and the Republic of South Sudan has not yet been determined. Final status of the Abyei area is not yet determined.

NOTE: Nitrogen (N) nutrient balances are calculated as the difference between inputs (synthetic fertilizers, manure, biological fixation, atmospheric deposition and seeds) and outputs (removal through harvest). Values below zero indicate soil nutrient impoverishment whereas positive balances above 80 kg/ha of N per ha suggest excessive applications.

SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Cropland nutrient balance. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/ESB. Licence: CC-BY-4.0.

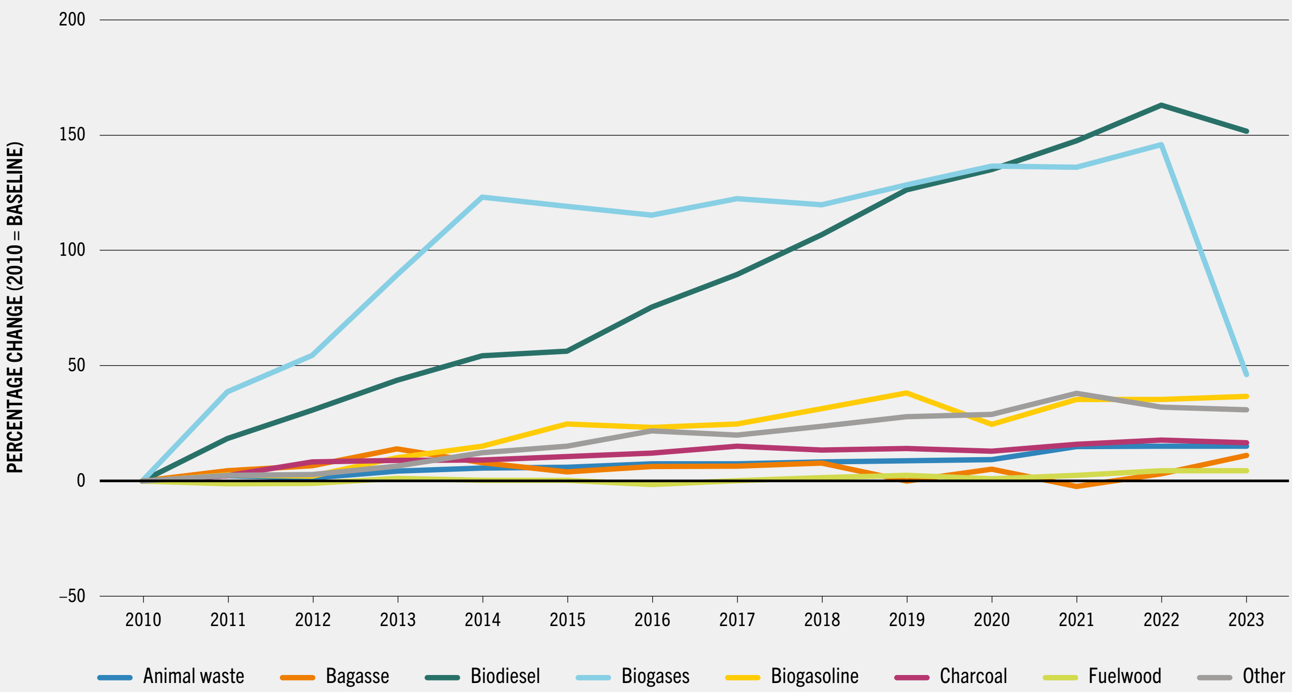
https://doi.org/10.4060/cd7488en-fig03

Since 2001, agricultural use of pesticides has increased by 60 percent, reaching a global average of 2.4 kg per hectare of cropland, with several countries using up to six times the world average (FAO, 2024c), constituting hotspots of environmental concern (Maggi, Tang and Tubiello, 2023). It is estimated that 64 percent of agricultural land is at risk of pesticide pollution (Tang *et al.*, 2021). Of particular concern are pesticides whose ingredients include perfluoroalkyl and polyfluoroalkyl substances (PFAS), known as "forever chemicals". The presence of these high-risk contaminants can lead to significant economic losses in the event of contaminated food recalls and health hazards (Donley *et al.*, 2024). ■

COMPETITION FOR LAND

Various economic activities compete with agriculture for land. Often, the best agricultural land is flat (including alluvial plains) and situated close to human residential areas and markets. This land is also preferred for other uses such as housing and industry. In most places, urban expansion translates into loss of prime agricultural land (IPCC, 2019). Unplanned and unregulated urban expansion and peri-urban development are important drivers of land-use change in many countries. Globally, urban areas more than doubled in size in just two decades, growing from 33 Mha in 1992 to 71 Mha in 2015. This expansion consumed 24 Mha of some of the

FIGURE 4 TRENDS IN CONSUMPTION OF BIOENERGY, 2010–2023



SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Bioenergy. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/BE. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig04

most fertile croplands, 3.3 Mha of forestlands and 4.6 Mha of shrublands.

Total production of bioenergy has increased by more than 50 percent since 2000. In 2023, the consumption of biodiesel was 2.5 times greater than it was in 2010 (FAO, 2025b). The increasing production of bioenergy and the increasing demands suggest potential competition of land uses (see Figure 4). Additionally, in many parts of the world, the production of cash crops aimed at distant markets exacerbates pressure on land, soil and water resources and aggravates competition with production aimed at local consumption (FAO, 2023b). The production and use of biomass for energy represents an additional risk of land degradation, food insecurity and GHG emissions (IPCC, 2019). ■

WATER SCARCITY AND WATER SHORTAGES

Water scarcity – the imbalance between supply of and demand for freshwater – and water quality issues are increasingly threatening food systems, from agricultural production through food processing to households and consumers.

Rising incomes and urbanization lead to increased water demand from industry, energy and services. Increases in population and income, combined with changes in consumption patterns result in increased demand for food, feed and water (IPCC, 2019).

Since water is unevenly distributed around the world, its scarcity is felt most keenly in arid and semi-arid areas, where demand for irrigation water is high and resources are scarce. The challenge for these regions is to raise agricultural water productivity – that is, the benefits from agricultural systems relative to the amount of water used. The aim is to produce more food, income, livelihoods and ecological benefits per unit of water while reducing the social and environmental cost of water withdrawal. Essentially, it means growing more food or gaining more benefits with less water. ■

GROUNDWATER DEPLETION

In many countries and regions, pumping water for domestic, industrial and agricultural supply is exhausting recoverable groundwater storage. Globally, groundwater is an important source of water for irrigated agriculture and its share compared with surface water is increasing. This is especially the case in arid and semi-arid regions. Intensive exploitation of many principal continental aquifers and saline intrusion along highly productive coastal plains are evident. This leads to lower groundwater levels, increased pumping costs, and greater pollution and saline water intrusion, threatening aquifer sustainability and potable water supplies and limiting agricultural production. ■

POLLUTION AND SALINIZATION

Pollution and salinity pose a global challenge that has become more acute in both high- and low-income countries, undermining economic growth as well as socioenvironmental sustainability and people's health (FAO and UNEP, 2021; FAO, 2024c). When not managed correctly, agricultural practices can increase pollutant loads (nutrients, salts, sediments, agrochemicals and pathogens) in soil, groundwater, rivers and lakes. In many countries, agriculture is the main non-point source of water pollution. Agriculture can also be heavily impacted by poor water quality, leading to increased costs, lower profitability and potential health issues. ■

SAND AND DUST STORMS

Agricultural land, especially in drylands, is commonly affected by sand and dust storms that occur when strong, turbulent winds erode small particles from soil surfaces with little or no vegetation cover. Sand and dust storms adversely affect the yields and productivity of crops, trees, pastures and livestock. In addition to air pollution, soil material lifted into the atmosphere holds many microorganisms such as bacteria, fungi and viruses. Sand and dust storms directly affect the prospects for achieving 11 of the 17 Sustainable Development Goals (SDGs), thereby undermining efforts to achieve the 2030 Agenda for Sustainable Development (FAO, 2023c; UNCCD, 2022b). ■

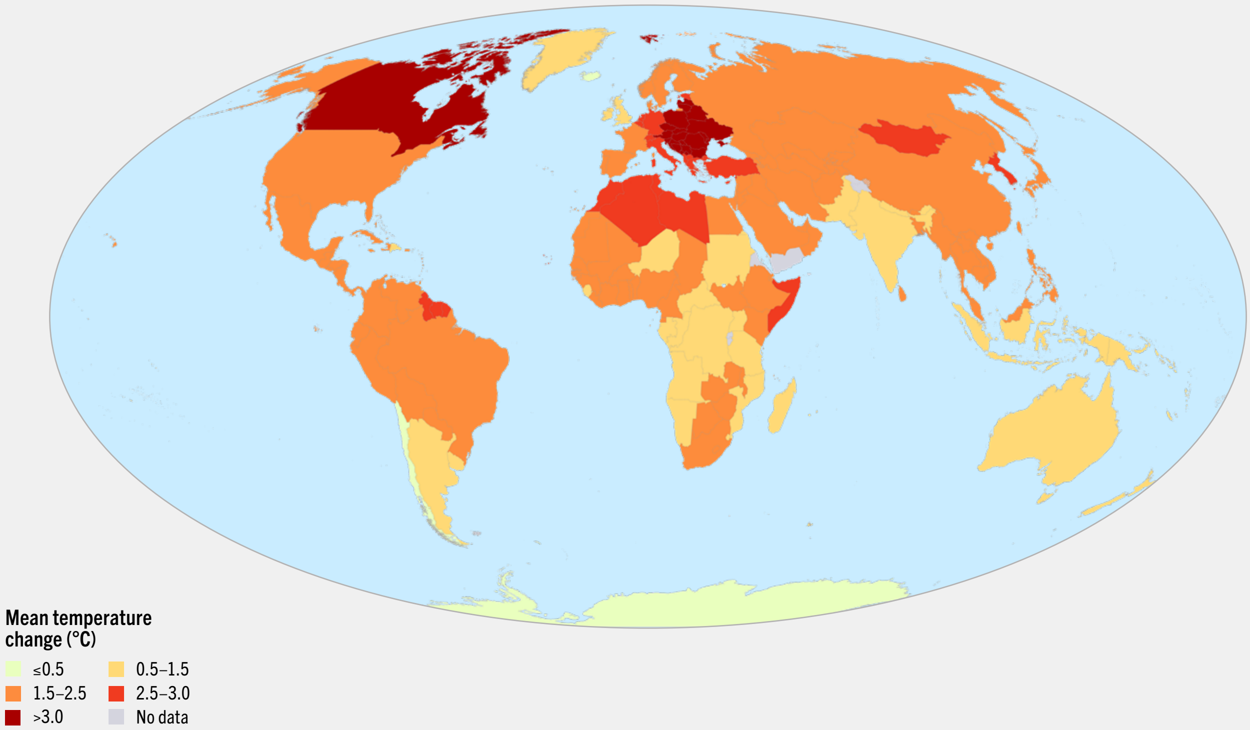
BIODIVERSITY LOSS

Biodiversity supports essential ecological processes that underpin agriculture. Loss of pollinators, natural pest control agents and soil organisms can lead to reduced crop yields and increased vulnerability to pests and diseases. For instance, a decline in pollinators can directly impact the production of many crops. Healthy soils, maintained by soil biodiversity, are crucial for water regulation and food production potential; loss of soil biodiversity can lead to soil degradation and reduced water retention. Unsustainable agricultural practices themselves contribute to biodiversity loss and can degrade land, further impacting productivity. Loss of biodiversity exacerbates the current trend for a growing dependence of global food production on a limited number of crop species. While more than 6 000 plant species have been cultivated for food, fewer than 200 make substantial contributions to global food output, with just 9 accounting for 66 percent of total crop production in 2014 (FAO, 2019). ■

CLIMATE CHANGE – AN EXISTENTIAL THREAT TO AGRIFOOD SYSTEMS

Agrifood systems – the production, distribution and consumption of food – are a major contributor to global warming and are responsible for

FIGURE 5 AVERAGE ANNUAL TEMPERATURE CHANGE BY COUNTRY, 2024



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 Sudan and the Republic of South Sudan has not yet been determined. Final status of the Abyei area is not yet determined.

NOTE: Temperature changes are measured on land, excluding ocean data, with reference to a climatology baseline 1951–1980.

SOURCES: Authors' own elaboration based on FAO. 2025. FAOSTAT: Temperature changes on land. [Accessed on 24 April 2025]. https://www.fao.org/faostat/en/#data/ET. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig05

one-third of total GHG emissions (FAO, 2023a). Direct emissions from manure and nitrogen applications to agricultural soils constitute the largest single source of nitrous oxide – a potent greenhouse gas and nowadays the first stratospheric ozone-depleting substance (UNEP and FAO, 2024).

At the same time, climate change affects all dimensions of food security, namely availability, access, utilization and stability, by disrupting food production, quality, storage, transport and retail activities. These effects exacerbate competition for land, soil and water resources (Bezner Kerr *et al.*, 2023).

Climate change contributes to land degradation through increases in rainfall intensity, flooding, drought frequency and severity (IPCC, 2019). It also affects soil carbon levels through warmer temperatures (Ren *et al.*, 2024) and altered precipitation patterns. In subtropical and tropical zones, climate-induced hazards such as floods and droughts negatively impact agricultural production. Vulnerable groups, including Indigenous Peoples, are disproportionally affected. They often rely on rainfed agriculture in marginal areas with high exposure and high vulnerability to water-related stress and low adaptive capacity (Caretta *et al.*, 2022).

FAO has estimated that in 2024, 5.4 billion people lived in countries experiencing temperatures that exceeded 1.5 °C above their baseline, and that 3.5 billion ha, corresponding to 73 percent of global agricultural area, were exposed to this warming (FAO, 2025c, 2025d). Figure 5 shows average temperature change by country in 2024 compared with the baseline of 1951–1980. The growing frequency and intensity of disasters caused by extreme weather events are taking an unprecedented toll on food production, with annual losses estimated at USD 123 billion, equivalent to 5 percent of global agricultural gross domestic product (GDP) (FAO, 2023d).

Hazardous weather events, including droughts, floods and heatwaves, disproportionately affect people living in low- and middle-income countries whose livelihoods closely depend on climate-exposed sectors such as agriculture (crop and livestock), forestry, fisheries and tourism (FAO, 2023d; IPCC, 2023). Land degradation exacerbates this situation by reducing the soil's capacity to retain water. Rural people living in poverty, women and the elderly are more severely affected (FAO, 2024d). Drought has been singled out as a major driver of crop yield reductions globally. Data drawn from reporting to the UNCCD by more than 100 countries have indicated that 1.84 billion people were drought-stricken in the biennium 2022–2023 (UNCCD, 2023). Since 2012, nearly 500 Mha of land have been affected by flood events each year and fires have burned a cumulative area of more than 24 Mha of land and vegetation (EM-DAT, 2024).

Climate change is intensifying the increasingly erratic water cycle, posing serious challenges to agriculture. As part of the contribution of Working Group II to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, Caretta *et al.* (2022) assessed, observed and projected climate-induced changes in the water cycle. The key findings can be summarized as follows:

- Extreme weather events causing highly impactful floods and droughts have become more likely and/or more severe due to climate change. Climate change has contributed to the increased likelihood and severity of the impact of droughts (especially agricultural and hydrological droughts) in many regions, and drought risks are projected to increase over the twenty-first century in many regions, increasing economy-wide risks.
- A large share of climate adaptation interventions (~60 percent) are shaped in response to water-related hazards and involve water interventions (irrigation, rainwater harvesting, soil moisture conservation). Irrigation helps stabilize and increase crop yields and is often a preferred strategy for risk reduction, but irrigation is also associated with a range of adverse outcomes, including groundwater overextraction and additional pressure on already scarce water resources. If not planned carefully, adaptation can transform into maladaptation. For example, efficient irrigation technologies like drip irrigation, while reducing water application rates per unit of land, can increase overall water extraction by increasing total land under irrigation.
- Several mitigation measures, such as carbon capture and storage, bioenergy and afforestation and reforestation, can have a high water footprint.
- Globally, 10 percent of the most water-stressed basins account for 35 percent of global irrigated calorie production. Food production is at risk in these basins and beyond, due to changes in the hydrological components of climate change (i.e. rainfall patterns and evapotranspiration requirements).
- Climate change also affects freshwater ecosystems, fish and other aquatic populations that have low buffering capacity and are sensitive to climate-related shocks and variability. ■

AFGHANISTAN
Farmers take an inventory of the pistachio forest rehabilitation and rangeland restoration activities initiated by FAO in Badghis Province.
© FAO/Sahil

CHAPTER 2
STATUS AND TRENDS IN THE MANAGEMENT OF LAND AND WATER RESOURCES

KEY MESSAGES

➔ Of all the economic sectors, agriculture, covering one-third of the world's land (4.8 billion ha), has by far the greatest impact on land resources. The situation is similar for water resources, with agriculture accounting for 72 percent of global water withdrawal.

➔ During the 60-year period between 1964 and 2023, most of the increase in agricultural production was due to intensification, with expansion of agricultural land limited to 8 percent. For example, the global increase of 213 percent in cereal production during that period was mostly accounted for by increased yields, with only 10 percent generated by an increase in harvested area.

➔ Intensification has been achieved through improved crop varieties, seeds and agronomic practices, better access to water and more systematic use of fertilizers. The area under irrigation more than doubled during that period and the use of fertilizers per hectare of agricultural land in 2023 was more than four times greater than in 1964.

➔ From 2001 to 2023, total agricultural land area decreased marginally: cropland increased by approximately 78 Mha (a 5 percent increase), while pastureland declined by 151 Mha (a 4 percent decrease).

➔ Middle and Eastern Africa saw the largest proportional increases in land used for the cultivation of temporary crops or arable land (+56 percent, +12.5 Mha, and +45 percent, +22 Mha, respectively),[c] followed by South America (+28 percent, +26 Mha). By contrast, Central and Northern America and Southern Europe recorded a net reduction in arable land between 2001 and 2023.

➔ Permanent crops, including oil palm, coffee, tea and other tree crops, increased by 42 percent (56 Mha) between 2001 and 2023, in nearly all regions and subregions. In most cases these crops serve the global market. In 2023, 22.5 percent of all croplands were equipped for irrigation and produced 48 percent of all crops in value terms. This indicates that irrigated land is 3.2 times more productive than rainfed land in value terms. On average, the yield of irrigated land is 76 percent more than that of rainfed land.

➔ Intensification has made it possible to limit further expansion of agricultural land (in some places, even reducing agricultural land) and encroachment on other lands.

➔ Increase in agricultural production, whether through expansion or intensification, has come at a high environmental cost, contributing to a substantial share of GHG emissions and biodiversity loss, degrading land and inland water ecosystems, polluting soils and aquifers, and pushing water withdrawal beyond sustainability limits in an increasing number of regions.

c For the full list of countries in these subregions, please refer to the table in the **Annex**.

➔ More than 1 660 Mha of land corresponding to more than 10 percent of the world's land area have been degraded by unsustainable land-use and management practices, and more than 60 percent of this degradation occurs on agricultural lands (including cropland and pastureland).

➔ Approximately 1.2 billion people, or about one-sixth of the global population, live in agricultural areas with severe water constraints.

➔ Further efforts are essential for more efficient use of water, and to ensure that water withdrawal – either from surface water or groundwater – takes place within the limits of sustainability.

➔ Future agricultural development pathways need to be based on the transformation of agrifood systems for better production, better nutrition, a better environment and a better life, leaving no one behind. The additional production required to satisfy the future increase in demand must be realized through more efficient, inclusive, resilient and sustainable production systems that address socioeconomic and environmental dimensions of sustainable development.

THE EXTENT OF CROPLAND IN THE WORLD

Measuring the extent and geographical distribution of cropland and the current performance of crop production around the world is crucial to assess the potential for further increases in food production and to monitor the sustainability of agriculture. In the recent past, considerable progress has been made in earth observation technologies, improving the ability to monitor agriculture at all scales and in near real time. However, discrepancies still exist among available cropland assessments (Tubiello *et al.*, 2023a, 2023b). A Cropland Agreement Map (CAM) has been produced, comparing six freely available global cropland maps at 10–30 m resolution (Tubiello *et al.*, 2022). A CAM can be interpreted as a probability map, where each pixel value shows how many datasets agree on the presence of cropland. This directly addresses uncertainty in cropland mapping by quantifying consensus across sources. The CAM was integrated into the land cover layer of the Global Agro-Ecological Zoning (GAEZ v5) (FAO and IIASA, 2025a, 2025b), providing a reliable cropland baseline for the land suitability analysis presented in this report as shown in Figure 6 (see also **Chapter 3**). ■

EVOLUTION OF AGRICULTURAL LAND USE

In 2023, agricultural land occupied more than one-third of the world's land area, amounting to approximately 4.8 billion ha (FAO, 2025a).[d] This area was divided into cropland, and permanent meadows and pastures, constituting about one-third and two-thirds of agricultural land, respectively. These two components have exhibited changes in opposite directions: cropland increased by approximately 78 Mha, representing a 5 percent increase between 2001 and 2023, while the area used for pastures declined by 151 Mha, a 4 percent decrease over the same period. As a result, the total agricultural land area has decreased marginally since 2001 (FAO, 2025a).

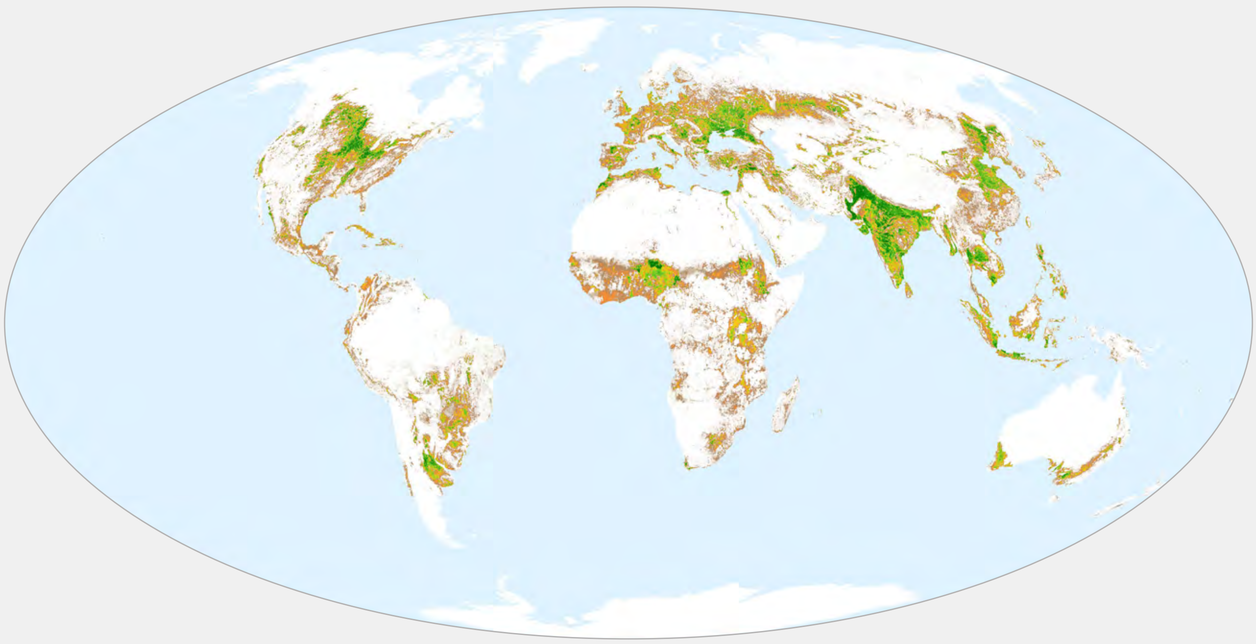
According to FAO land-use definitions, cropland is further divided into arable land and permanent crops, which accounted for 1 381 and 191 Mha, respectively, in 2023. Arable land is land used for the cultivation of temporary crops – crops with an annual cycle – such as wheat and maize, in rotation with fallow land and temporary pastures in management cycles of up to five years. The interplay of these components over time determines the patterns of land-use change (see Figure 7).

Within cropland, the net expansion of arable land is typically driven by the increase in temporary crops and is often accompanied by a reduction in the area left fallow (see Figure 8).

Across regions, increases in arable land were recorded in Africa (+28 percent, corresponding to

d FAO's Corporate Database for Substantive Statistical Data (FAOSTAT) defines "agricultural land" as land used for cultivation of crops and animal husbandry, and it is made up of the total of areas under cropland and permanent meadows and pastures. "Cropland" is land used for cultivation of crops and comprises the total of areas under arable land and permanent crops. "Arable land" is land used for cultivation of crops in rotation with fallow, meadows and pastures within cycles of up to five years. "Permanent meadows and pastures" refers to land used permanently (five years or more) to grow herbaceous forage crops through cultivation or naturally (wild prairie or grazing land).

FIGURE 6 **DISTRIBUTION OF CROPLAND AREA, 2020**



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

NOTE: The figure shows the percent cropland class within the pixel area.

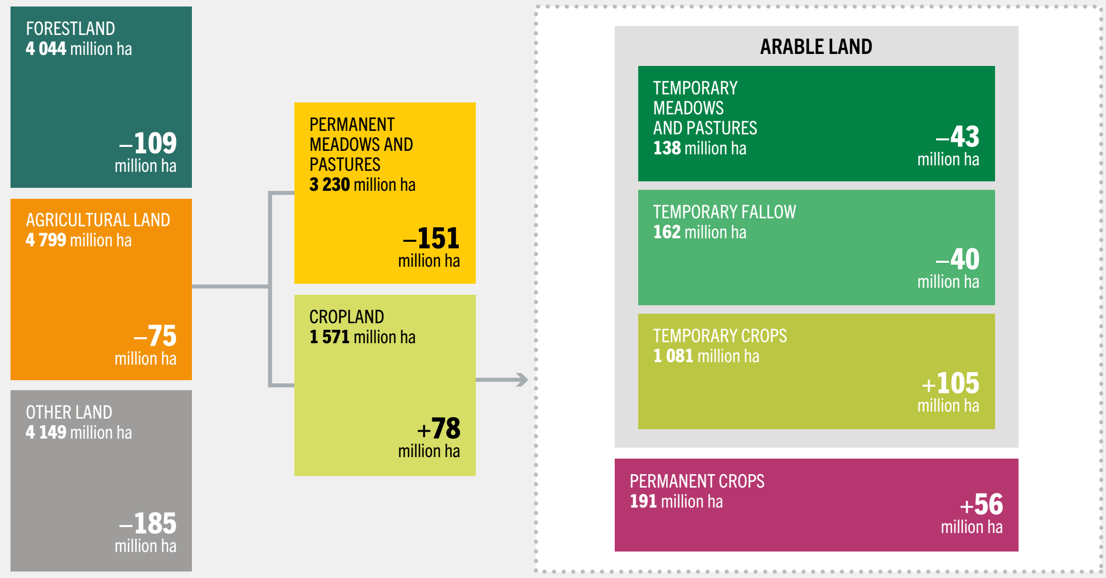
SOURCES: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en; FAO & IIASA. 2025. Share of land cover class (Global - ~1 km) – GAEZ v5. [Accessed on 13 February 2025]. https://data.apps.fao.org/catalog/iso/f7bee2f1-3a48-4e86-a1d2-387023dec046. Licence: CC-BY-4.0.

an additional 57 Mha) and Oceania (+28 percent, +7 Mha), while the other regions exhibited marginal reductions. All regions except Oceania exhibited a decline in the area left fallow. In Africa, more than elsewhere, this reduction was accompanied by a significant increase in the area under temporary crops (+38 percent, +59 Mha). Across the subregions, Middle Africa (+56 percent, +12.5 Mha), Eastern Africa (+45 percent, +22 Mha), Australia and New Zealand (+28 percent, +7 Mha) and South America (+28 percent, +27 Mha) had the largest proportional growth in arable land. By contrast, Central and Northern America, Southern and Eastern Europe, and Eastern Asia recorded a net reduction in arable land between 2001 and 2023. In Eastern Europe, the increase in temporary crops was counterbalanced by a reduction in temporary fallow and pastures, resulting in a marginal decrease in total arable land (FAO, 2025a).

Permanent crops, including oil palm, coffee, tea and other tree crops, increased by 42 percent or 56 Mha between 2001 and 2023 in all regions and subregions of the world except Europe. In most cases, these crops serve the global market. The largest proportional increments were recorded in Middle and Western African and Eastern and South-eastern Asia.

According to FAO, human activities have already degraded 1 660 Mha of land due to unsustainable land-use practices (FAO, 2021). More than 60 percent of this degradation occurs on »

FIGURE 7 COMPONENTS OF THE WORLD'S LAND USE AND NET CHANGES, 2001–2023



SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 1 July 2025].
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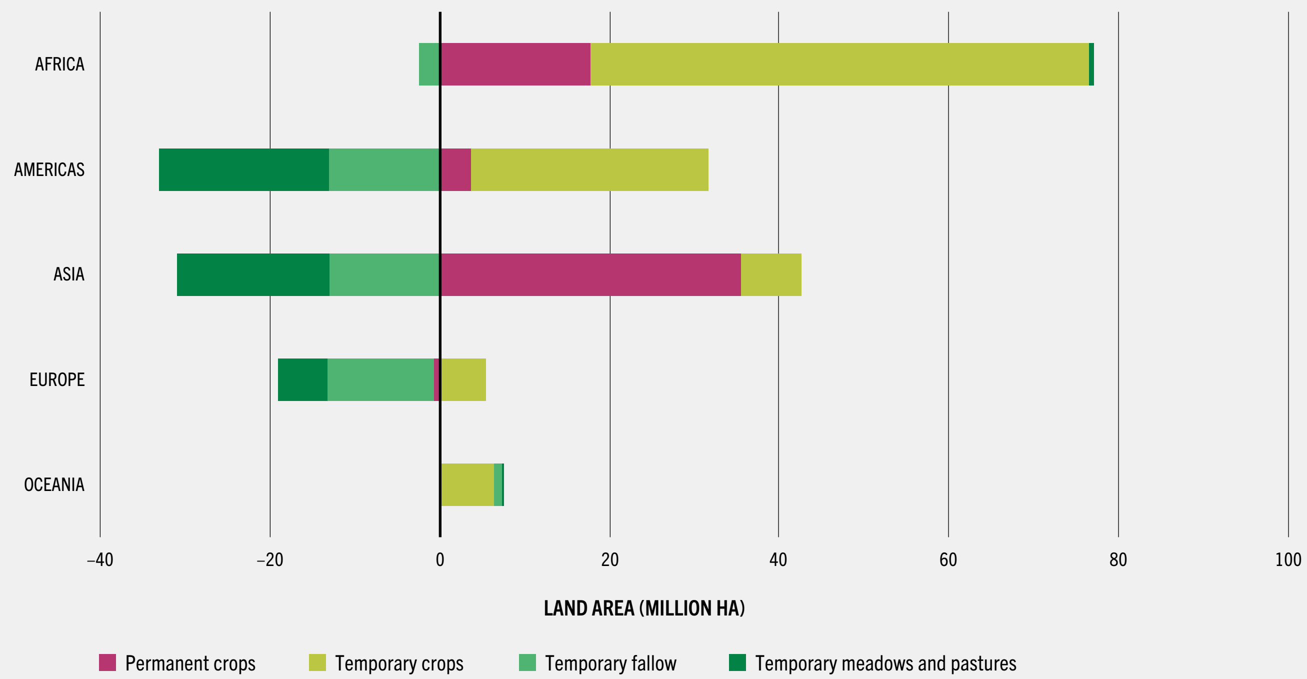
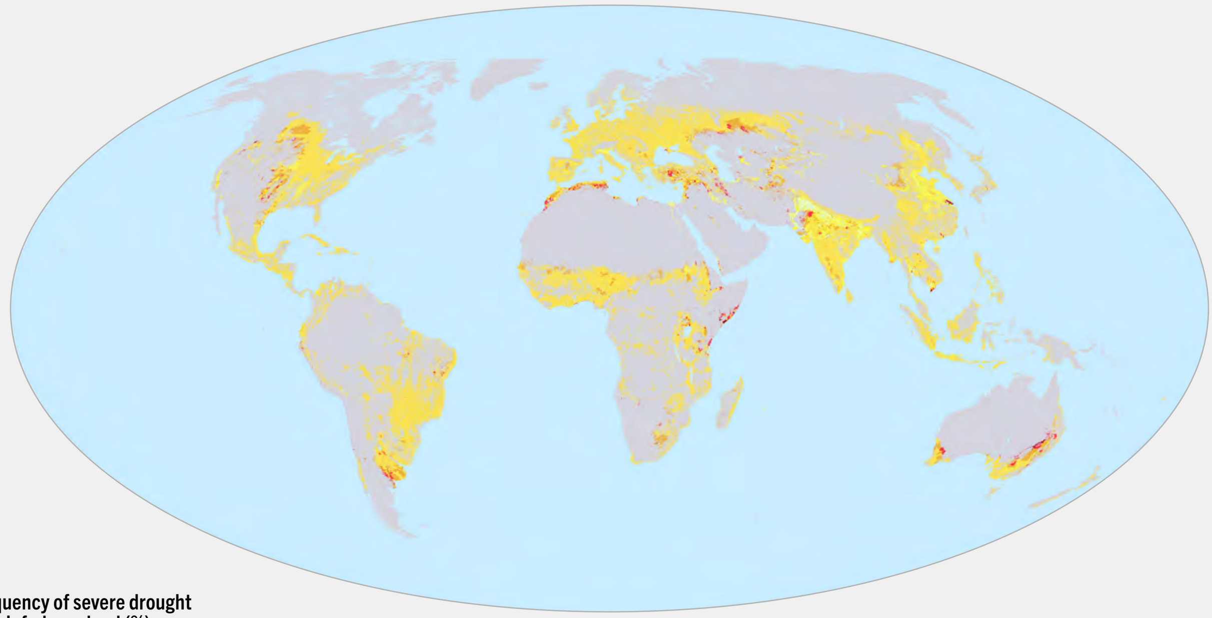
FIGURE 8 NET CHANGE IN CROPLAND AREA BY REGION AND LAND-USE COMPONENT, 2001–2023



SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 1 July 2025].
https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig08

FIGURE 9 HISTORICAL DROUGHT FREQUENCY ON RAINFED CROPLAND, 1984–2023



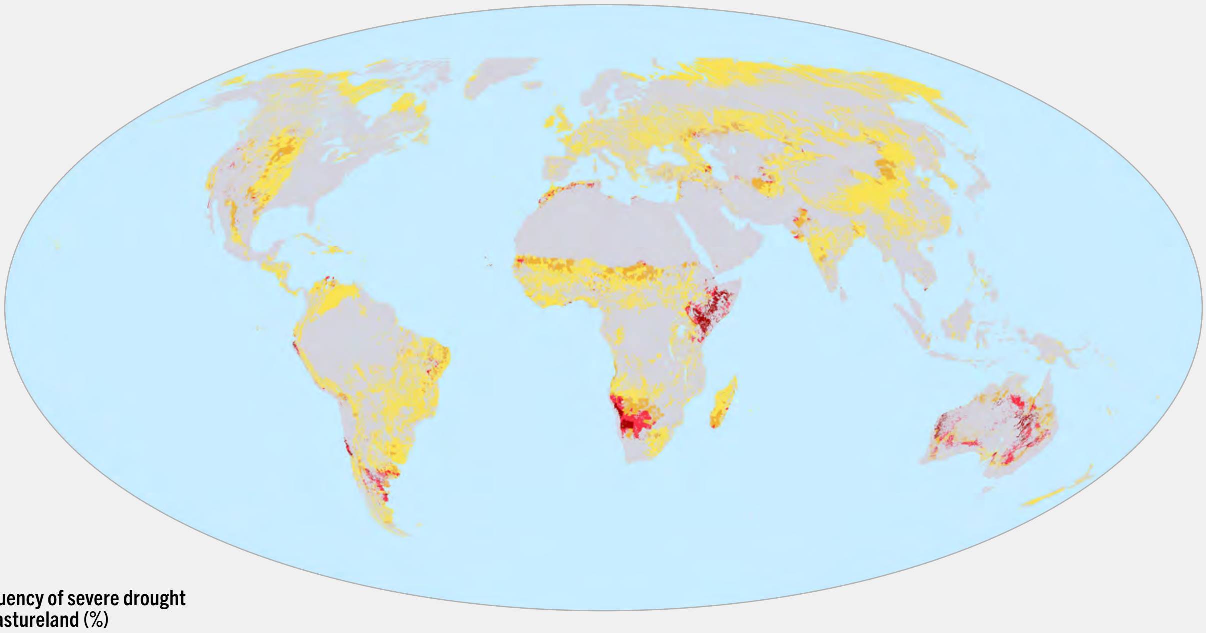
Frequency of severe drought on rainfed cropland (%)

≤10 | 10–20 | 20–30 | >30 | No data | No rainfed cropland

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

SOURCES: Authors' own elaboration based on the methodology in FAO. 2020. *The State of Food and Agriculture 2020 – Overcoming water challenges in agriculture*. Rome. https://doi.org/10.4060/cb1447en; data from Historic agricultural drought frequency (Global – 1 km) – FAO ASIS. [Accessed on 23 July 2025]. https://data.apps.fao.org/catalog/iso/f8568e67-46e7-425d-b779-a8504971389b. Licence: CC BY-SA 4.0.

FIGURE 10 HISTORICAL DROUGHT FREQUENCY ON RAINFED PASTURELAND, 1984–2023



Frequency of severe drought on pastureland (%)

≤10 | 10–20 | 20–30 | >30 | No data

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

SOURCES: Authors' own elaboration based on the methodology in FAO. 2020. *The State of Food and Agriculture 2020 – Overcoming water challenges in agriculture*. Rome. https://doi.org/10.4060/cb1447en; data from Historic agricultural drought frequency (Global – 1 km) – FAO ASIS. [Accessed on 23 July 2025]. https://data.apps.fao.org/catalog/iso/f8568e67-46e7-425d-b779-a8504971389b. Licence: CC BY-SA 4.0.

TABLE 1 VARIATION IN AREA, YIELD AND PRODUCTION OF CEREALS BY REGION, 1964–2023

Region	Variable	Variation (%)			
		1964–1983	1984–2003	2004–2023	1964–2023
Africa	Area harvested	7	52	33	112
	Yield	20	32	22	99
	Production	28	101	62	322
Americas	Area harvested	6	–12	11	12
	Yield	34	37	23	194
	Production	42	20	36	228
Asia	Area harvested	9	3	9	21
	Yield	75	27	35	221
	Production	91	30	47	290
Europe	Area harvested	–6	–38	–8	–42
	Yield	54	27	19	199
	Production	45	–21	10	74
Oceania	Area harvested	91	–4	–9	85
	Yield	24	–35	52	141
	Production	137	–38	39	345
WORLD	Area harvested	**5**	**–6**	**9**	**10**
	Yield	**55**	**24**	**26**	**184**
	Production	**62**	**16**	**37**	**213**

SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Crops and livestock products. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

» agricultural lands, including both cropland and pastureland (FAO, 2021, 2025b; Ziadat *et al*., 2025).

In the past 40 years, on a global scale, droughts have impacted people more than any other natural disaster. About 128 Mha (11 percent) of rainfed cropland (see Figure 9) and 656 Mha (14 percent) of pastureland (see Figure 10) frequently experience droughts (FAO, 2020). The intensity, duration, frequency and spatial extent of droughts are expected to increase due to climate change and rising temperatures. This will translate into an even greater burden on farmers if land degradation is not halted and reversed. Reports to the UNCCD from more than 100 countries revealed that 1.84 billion people were affected by droughts in the 2022–2023 biennium (UNCCD, 2023). ■

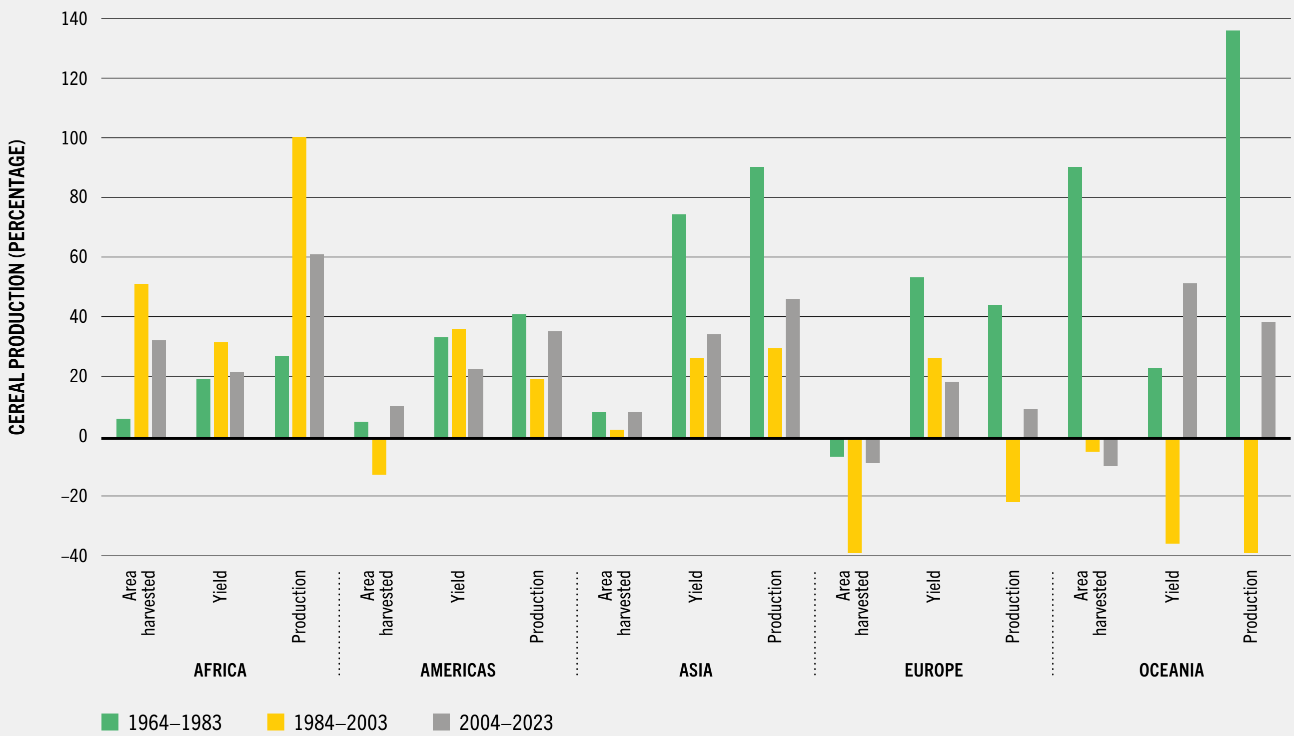
PAST PERFORMANCE OF AGRICULTURAL SYSTEMS

There are three ways to increase crop production: expanding areas under production, increasing crop yields, and increasing cropping intensity;[e] the latter two also contribute to intensification (more production per unit of land).

In the case of cereals – the prevailing staples – production over the past 60 years (1964–2023) increased by 213 percent globally (see Table 1). The harvested area increased over the same period by only 10 percent, while yields increased by 184 percent. This implies that yield increases accounted for 95 percent of the production increase, while area expansion accounted for just

e Cropping intensity is defined as the ratio of the sum of the harvested areas to total cropland for a given area, region or country in a year. Cropping intensity can be higher than 100 percent when more than one crop is grown on the same land over an agricultural year.

FIGURE 11 SOURCES OF VARIATION IN CEREAL PRODUCTION, 1964–2023



SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Crops and livestock products. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig11

5 percent. These percentage differ over space and time. In Europe, the production increase was entirely due to increases in yields, which more than tripled, while the harvested area was reduced by over 40 percent. In Africa, the production increase was due to a combination of yield increase (nearly 100 percent) and area expansion (112 percent), with harvested area more than doubling during this period.

In terms of time, the largest relative yield increase occurred in the period 1964–1983, with an average global yield increase of 55 percent. In the periods 1984–2003 and 2004–2023, the relative yield increase over 20 years was around 25 percent in each case (see Figure 11).

Cropping intensity is another source of production increase. The ratio of harvested area to arable land gives an indication of the cropping intensity for a given period. Table 2 shows that globally there was an increase of 26 percent in cropping intensity in the period 1964–2023. Increases in Africa and the Americas were the highest, while in Asia the increases were low, and negative in the case of Europe.

Data on cropping intensities per crop are not available at country level. Based on Table 2, and assuming the same cropping intensity for cereals, Table 3 provides an estimate of the change in extent of cereal cropland over the period 1964–2023.

Globally, these figures would suggest that, with a cropping intensity of 75 percent in 1964, cropland under cereals would be 890 million ha, with a harvested area of over 667 Mha. In 2023, with a cropping intensity of 95 percent, cereal cropland would be 780 Mha and the area harvested 741 Mha. Therefore, while the production of

TABLE 2 VARIATION IN CROPPING INTENSITY (ALL CROPS), 1964–2023

Region	Harvested area		Cropland		Cropping intensity (CI)		Change in CI
	million ha				%		
	1964	2023	1964	2023	1964	2023	
Africa	113	307	171	307	66	100	52
Americas	188	315	325	369	58	85	48
Asia	431	654	450	575	96	114	19
Europe	273	184	386	286	71	64	–9
Oceania	12	29	18	34	65	85	32
WORLD	**1 016**	**1 488**	**1 350**	**1 571**	**75**	**95**	**26**

SOURCES: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0; FAO. 2025. FAOSTAT: Crops and livestock products. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

TABLE 3 ESTIMATE OF LAND USED FOR CEREAL PRODUCTION, 1964–2023

Region	Cereal cropland		Variation
	million ha		%
	1964	2023	
Africa	91	128	40
Americas	213	161	–24
Asia	294	301	2
Europe	277	177	–36
Oceania	15	22	40
WORLD	**890**	**780**	**–12**

SOURCES: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0; FAO. 2025. FAOSTAT: Crops and livestock products. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

cereals over the 60 years between 1964 and 2023 more than tripled, the area harvested increased by 11 percent and the cropland under cereals declined by 12 percent.

For most cereals, it is likely that the global production increase is due solely to agricultural intensification. This is unsurprising given that most agricultural research over the period 1964–2023 focused on staple crops in general, and cereals in particular.

Overall, agricultural land increased globally by a mere 8 percent between 1963 and 2023 (see Table 4). This increase should be mainly attributed to the 16 percent increase in cropland, compared with an increase in permanent meadows and pastures of just 4 percent (see Table 5). The increase in permanent crops (not shown in the table) was higher than the increase in annual crops.

Table 6 and Figure 12 show the role of irrigation and fertilizer in agricultural intensification. The area under irrigation more than doubled between 1964 and 2023 and the use of fertilizers per hectare of cropland in 2023 was more than four times greater than in 1964. ■

TABLE 4 CHANGE IN EXTENT OF AGRICULTURAL LAND, 1964–2023

Region	Agricultural land		
	1964	2023	Variation
	million ha		%
Africa	1 012	1 175	16
Americas	1 083	1 139	5
Asia	1 083	1 653	53
Europe	779	457	–41
Oceania	497	375	–24
WORLD	**4 454**	**4 799**	**8**

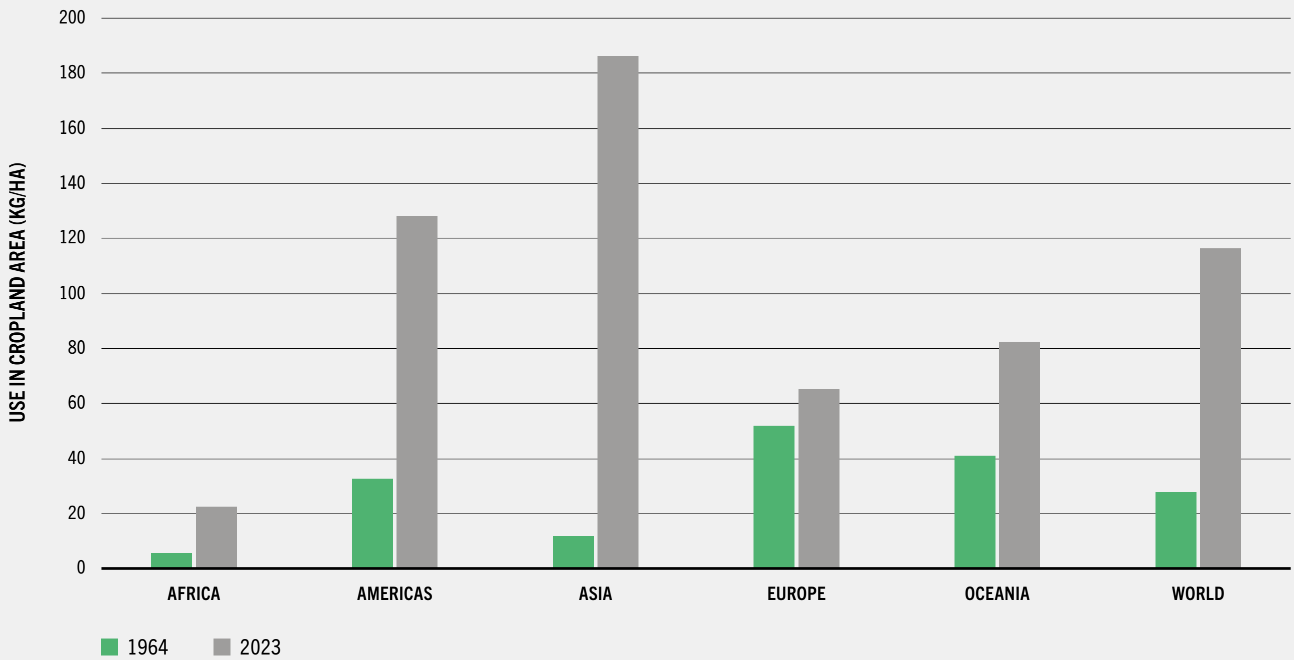
SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0.

TABLE 5 CHANGE IN EXTENT OF AGRICULTURAL LAND BY LAND-USE CATEGORY, 1964–2023

Region	Cropland			Arable land			Permanent meadows and pastures		
	1964	2023	Variation	1964	2023	Variation	1964	2023	Variation
	million ha		%	million ha		%	million ha		%
Africa	171	307	79	155	262	69	841	869	3
Americas	325	369	14	307	341	11	757	770	2
Asia	450	575	28	426	475	12	633	1 078	70
Europe	386	286	–26	368	271	–26	393	172	–56
Oceania	18	34	89	17	32	89	479	342	–29
WORLD	**1 350**	**1 571**	**16**	**1 273**	**1 380**	**8**	**3 104**	**3 230**	**4**

SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0.

FIGURE 12 VARIATION IN THE USE OF FERTILIZERS IN CROPLAND, 1964–2023



SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Fertilizers by nutrient. [Accessed on 15 July 2025]. https://www.fao.org/faostat/en/#data/RFN. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig12

TABLE 6 EVOLUTION OF LAND EQUIPPED FOR IRRIGATION, 1964–2023

Region	Land equipped for irrigation				Variation
	1964		2023		1964–2023
	1 000 ha	Share (%)*	1 000 ha	Share (%)*	(%)
Africa	7 492	4	17 524	6	134
Americas	29 635	9	55 384	15	87
Asia	109 132	24	251 090	44	130
Europe	20 120	5	27 651	10	37
Oceania	1 254	7	3 323	10	165
WORLD	**167 633**	**12**	**354 972**	**23**	**112**

NOTE: * Share of cropland.

SOURCE: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0.

CONTRIBUTION OF IRRIGATION TO GLOBAL CROP PRODUCTION

Irrigation plays a critical role in agricultural production. It ensures that crops benefit from adequate levels of soil moisture throughout the growing season. In so doing, it protects crops from the vagaries of climate, in particular the uncertainty associated with the volume and distribution of precipitations. In dry climates, irrigation is often an essential prerequisite for crop production (see Box 1).

Irrigation has substantial costs. Financially, the infrastructure and equipment needed to take water to fields represent a significant investment. Operation and maintenance costs are also relatively high compared with rainfed agriculture. In environment terms, irrigation is one of the main causes of water scarcity in many regions; given that agriculture accounts for about 72 percent of global freshwater withdrawals, it represents a substantial challenge to sustainable water management.

Assessing the costs and benefits of irrigation is therefore critical. In terms of benefits, the parameter often used is the contribution of irrigation to crop production. Whether this assessment is conducted at local, country or global level, the contribution of irrigation to crop production, and therefore to agriculture, is a key element to consider in agricultural policies.

Global statistics on irrigated production are scarce. FAO's statistical database FAOSTAT offers a range of data on agricultural land and agricultural production by country, including the value of main agricultural commodities. FAO's Global Information System on Water and Agriculture (AQUASTAT) offers a combination of data and information on irrigated agriculture for developing countries, as well as regional overviews. Country and regional profiles include data on the extent of irrigated crops.

For this report, FAOSTAT and AQUASTAT data were used to estimate the contribution of irrigation to global crop production for the reference year 2022. A combination of regions and major agricultural countries were studied, representing 83 percent of the world's cropland. The results of this analysis are presented in Table 7.

In 2022, 22.5 percent of all croplands were equipped for irrigation. These irrigated croplands produced 48 percent of all crops in value terms. This indicates that irrigated land is 3.2 times more productive than rainfed land. As previously mentioned, there are various factors that explain this difference, in particular: higher yields, the potential for increasing cropping intensity, and the fact that irrigation is systematically used to grow high-value crops. The study on irrigated and rainfed croplands

BOX 1 HOW IRRIGATION CONTRIBUTES TO CROP PRODUCTION

- **Higher yields.** Irrigated crops often yield more than rainfed ones, depending on crop type, region and water management. Estimates range from 30 to 300 percent more yield with irrigation than with rainfed cultivation. There is no real upper limit, as irrigation is often practised in arid areas where rainfed production would not be possible.
- **Crop diversification and risk management.** Irrigation enables farmers to grow high-value crops such as fruits, vegetables and spices while protecting them from excessive variations in precipitation. In particular, most vegetables require constant soil moisture, a situation that cannot be guaranteed in rainfed conditions.
- **Double/triple cropping.** Climatic conditions in many areas restrict cropping to part of the year, when rainfall is abundant. Irrigation allows farmers to boost production by using their land even during dry periods, thereby increasing cropping intensity.
- **Stability, resilience and climate adaptation.** Irrigation reduces the risk of crop failure due to drought or erratic rainfall. As such, it provides more predictability regarding production and incentivizes producers to invest in inputs such as nutrients or protection against pests and diseases, thus indirectly increasing yields. As rainfall patterns become more erratic due to climate change, the stabilizing role of irrigation is increasingly important.

TABLE 7 IRRIGATED AND RAINFED LAND BY REGION, AND THE RELATIVE PRODUCTION VALUE

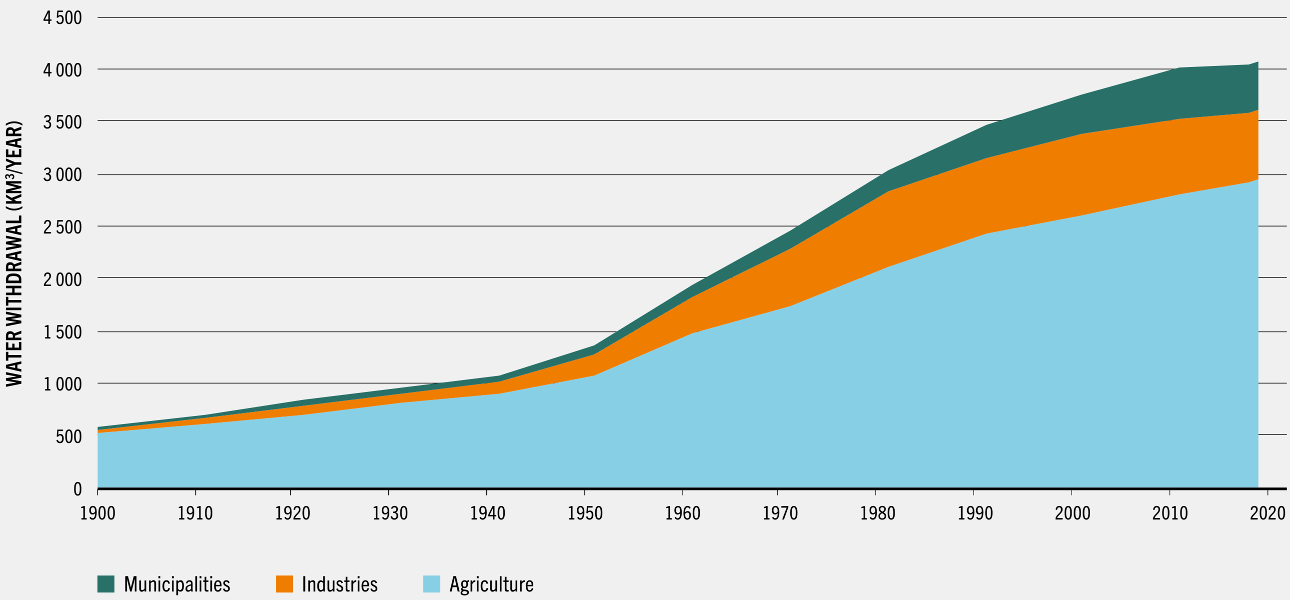
Region/country	Land area (million ha)		Production value (billion USD)	
	Rainfed	Irrigated	Rainfed	Irrigated
Total (based on 83 percent of global cropland in 2022)	**1 016**	**296**	**1 315**	**1 222**
Percentage	**77.5**	**22.5**	**52**	**48**
Africa	94	6	88	12
Asia*	55	45	43	57
Latin America and the Caribbean	88	12	59	41
United States of America	83	17	57	43
Russian Federation	97	3	91	9
Central Asia	73	27	61	39
Others**	83	17	44	56

NOTES: * Eastern, Southern and South-eastern Asia (excluding Japan). ** Canada, France, Islamic Republic of Iran, Japan.

SOURCES: Authors' own elaboration based on FAO. 2025. FAOSTAT: Land use. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0; FAO. 2025. AQUASTAT. [Accessed on April 2025]. https://www.fao.org/aquastat/en/databases. Licence: CC-BY-4.0.

conducted for this report estimates that, on average, the yield of irrigated production is 76 percent more than that of rainfed production. Cropping intensity in irrigated agriculture is estimated to be 25 percent higher than in rainfed agriculture. Finally, the value of irrigated production is 45 percent higher on average than the value of rainfed production. These figures are global estimates. Large differences are noted between countries and regions, according to the climatic conditions and the relative expansion of irrigation in agriculture. ■

FIGURE 13 **EVOLUTION OF GLOBAL SECTORAL WATER WITHDRAWALS, 1900–2020**



SOURCES: Authors' own elaboration based on FAO. 2020. *The State of Food and Agriculture 2020 – Overcoming water challenges in agriculture*. Rome. https://doi.org/10.4060/cb1447en

https://doi.org/10.4060/cd7488en-fig13

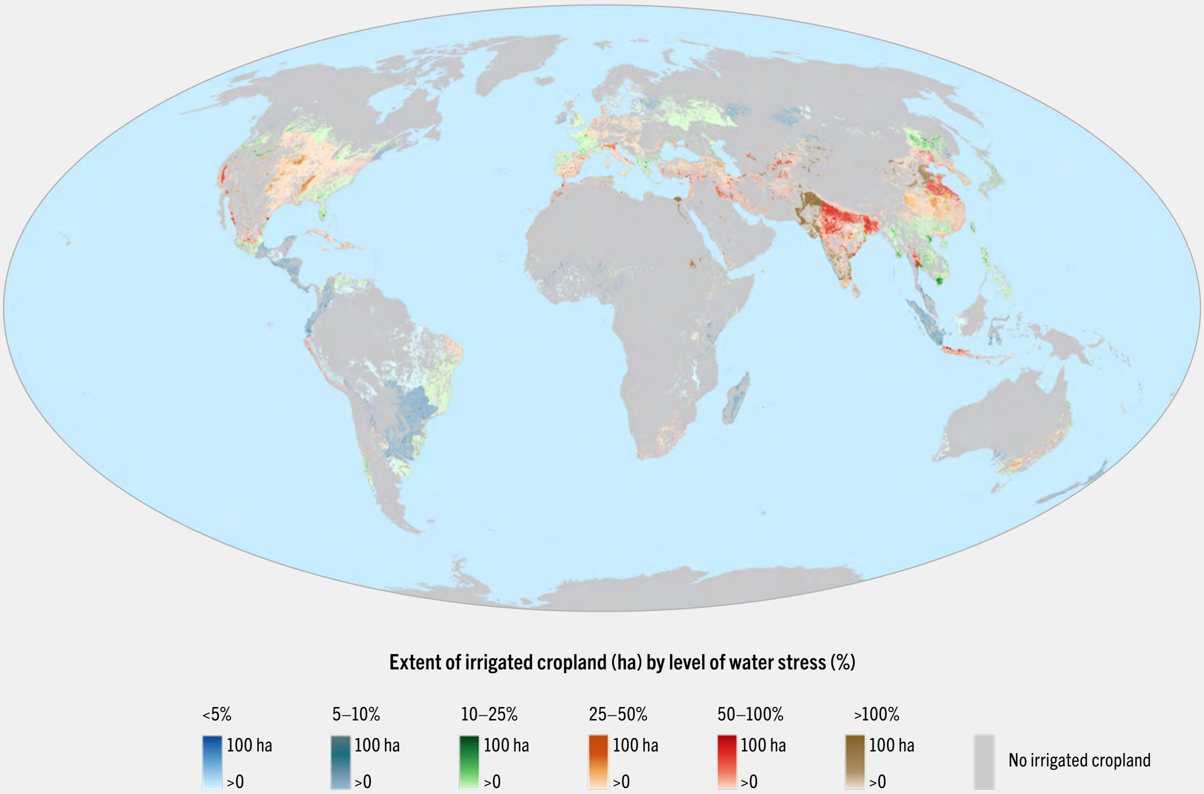
THE CURRENT STATUS OF WATER RESOURCES FOR AGRICULTURE

Globally, agriculture is the dominant sector in terms of freshwater withdrawals, representing 72 percent of total freshwater withdrawals in 2020, followed by the industrial sector at 16 percent and the service sector at 12 percent (FAO, 2020; Figure 13). While overall growth in water withdrawal is slowing, agricultural water withdrawal continues to rise, reflecting the continuous increase in areas under irrigation. The rapid rise in levels of water withdrawal over the past decades has resulted in a growing number of regions becoming subject to increased water stress.

Approximately 1.2 billion people, or about one-sixth of the global population, live in agricultural areas with severe water constraints. (FAO, 2020).

In Southern Asia, about 520 million people live in agricultural areas with severe water constraints, while in Eastern and South-eastern Asia, the number is approximately 460 million. This means that in both regions more than 40 percent of rural people live in areas with water constraints. In Central Asia, Northern Africa and Western Asia, around 20 percent of the population live in areas with significant water shortages or scarcity. By contrast, only 1 to 4 percent of the population in Europe, Latin America and the Caribbean, Northern America and Oceania face extreme water constraints. In sub-Saharan Africa, about 5 percent of the population live in affected areas, primarily due to severe droughts and lack of irrigation infrastructure. Although 5 percent might seem a small share, it translates into roughly 50 million people living in areas where

FIGURE 14 SDG INDICATOR 6.4.2 – LEVEL OF WATER STRESS ON IRRIGATED AREAS, 2018



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

SOURCES: Authors' own elaboration based on methodology from FAO. 2020. *The State of Food and Agriculture 2020 – Overcoming water challenges in agriculture*. Rome. https://doi.org/10.4060/cb1447en; data from Level of water stress (SDG 6.4.2) by major river basin (reference year 2018). [Accessed on 1 August 2025]. https://data.apps.fao.org/catalog/iso/40bc32f6-1467-44ac-8f7c-3d67cbb1cbd7. Licence: CC-BY-NC-SA 3.0 IGO.

severe droughts have devastating impacts on cropland and pastureland (FAO, 2020).

It is estimated that 171 million ha – more than 60 percent of irrigated croplands – are under high or very high levels of water stress (see Figure 14).

To satisfy the needs of a growing and increasingly wealthy world population with changing diets (including more meat) and meet the increased demand for feeds and other agricultural products – accompanied by growing quantities of convenience food and, most likely, more food waste at the consumer level – agriculture will require more water than it currently uses. Evapotranspiration from irrigated land was estimated at 1 285 km^3 and could increase by 20 to 30 percent by 2050, taking into account both biophysical effects such as climate change and the above-mentioned socioeconomic factors. The increase in water withdrawals for agriculture will probably be less than the expected increase in evapotranspiration – since irrigation efficiencies and land and water productivity will likely increase significantly. However, this will require a combination of technological and managerial solutions, and an enabling policy and governance environment. These solutions are discussed in **Chapter 4** and **Chapter 5**. ■

THAILAND
Cultivation of pepper seedlings using a drip irrigation system to optimize water and nutrient use.
© Kheartmanee Thongyot

CHAPTER 3
PRODUCING MORE AND BETTER: THE POTENTIAL

KEY MESSAGES

➔ The potential exists to feed the 9.7 billion people predicted to make up the world's population by 2050, and the approximately 10.3 billion people when the global population is projected to peak around 2085. The conditions under which this food production takes place will determine the associated environmental, social and economic costs.

➔ With a total of more than 4 billion ha globally, a substantial amount of land is suitable for cultivation. However, the potential for agricultural expansion is limited, as further land conversion to cropland would impact other ecosystems, including forests, grasslands and wetlands.

➔ It should be emphasized that the assessment of land suitability for cultivation is based only on the characteristics of the land and does not consider existing land use and whether any conversion to cropland is acceptable. For instance, expansion of agriculture into existing forests is in most cases not a strategic option, even when that land offers high levels of suitability for cultivation. This report offers some proposals of alternative suitable areas for cropping to enhance food production and, at the same time, protect forestlands and protected areas.

➔ Land suitable for crop cultivation is not distributed evenly across the world, with regions such as Africa and South America showing opportunities for further expansion, while other regions such as the Near East have mostly reached their limit, and in some cases are experiencing a reduction in area under agriculture.

➔ Most agricultural production is practised on prime or good agricultural land. However, there are areas where population pressure and limited resources force farmers to practise agriculture on marginal land.

➔ Intensification is key: efforts to meet future demand for food must above all involve a more efficient, sustainable and productive use of existing agricultural land. It is critical to ensure that intensification is pursued in a far more sustainable manner than in the past.

➔ There is scope for significant increases in land productivity in most developing regions and for most types of crops. The bulk of increased food production should come from reductions in yield gap, the selection of crops suitable for agroecological conditions, and the adoption of sustainable management practices adapted to each crop.

➔ It is possible to enhance the productivity of marginal land by adopting practices that address factors limiting their potential. Such practices must be adapted to local conditions and need to be supported by appropriate financial and policy instruments.

➔ Among the solutions that can enhance the potential of land to increase crop production, irrigation and other water harvesting techniques can alleviate constraints related to soil moisture by ensuring an adequate water supply to crops. There is substantial scope for further increases in water productivity for agriculture, but much less for increases in water use, particularly in arid regions. Potential increases in water use need to be assessed not only at farm level, but also at river basin and aquifer levels to ensure sustainability.

➔ The availability and quality of soil nutrients is a major constraint limiting production in many areas. This issue can be addressed by introducing better agricultural practices: nutrient-use efficiency; balanced fertilization with integration of organic inputs to avoid the underuse, misuse and overuse of fertilizers; sustainable use of fertilizers; mechanization; adoption of adapted crop varieties; and promotion of agrobiodiversity including the cultivation of opportunity crops adapted to specific conditions and cultures.

➔ Climate change affects land suitability for many crops, with suitable areas for given crops usually moving to higher latitudes and altitudes. For some crops, agricultural water demand will increase in future climate scenarios, while the available water resources will become more variable and less reliable.

➔ In areas where land and water resources are scarce, satisfying competing societal objectives (agriculture, industry, urban development, energy, biodiversity conservation) often implies trade-offs and difficult choices in resource allocation. Integrated land and water resource planning provides tools to manage the competition for resources and optimize resource use.

➔ In degraded agricultural lands, there is scope for restoring the production potential to increase production and productivity using sustainable management practices and techniques, while also addressing and eliminating the root causes and drivers of land degradation.

➔ Land use is determined by a combination of biophysical and socioeconomic factors, including demography, market, land tenure and policies, and does not necessarily respond to technocratic land-use planning logics. At global level, trade will continue to compensate for the increasing discrepancy between production capacity and demand for agricultural products.

This chapter discusses the potential for increasing production and productivity of agricultural land to respond to the increasing demand for food and other agricultural products and the environmental and socioeconomic challenges described previously. It focuses primarily on crop production, the primary source of food, for which advanced modelling capacities exist. **Chapter 4** and **Chapter 5** discuss the technical, policy and institutional measures needed to realize this potential.

An increase in agricultural production can be achieved either through an expansion of agricultural activity (increasing the land area used for farming, if possible and without compromising other ecosystems) or through intensification (increasing production on existing agricultural land). In turn, intensification can be achieved through an increase in the yield of a given crop or in the number of times the land is used during the year (cropping intensity), or through a combination of both. Given the scale of degradation of agricultural land (cropland and pastureland) discussed in **Chapter 2**, the restoration of degraded agricultural lands and soils could significantly contribute to intensification (increasing production on existing agricultural land).

In many regions, crop yields fall short of those that could be obtained with appropriate management. The difference between actual yield and attainable yield is known as the "yield gap". For example, in sub-Saharan Africa, the yield of rainfed crops is only 24 percent of that possible if appropriate management practices were adopted (FAO, 2022). Knowing the extent and geographical distribution of yield gaps is essential in order to develop strategies for enhanced production: comparing actual and attainable crop yields makes it possible to identify areas where an increase in food production is achievable through improved management practices.

Yield gaps and the potential of land to increase production were analysed for cropland under rainfed and irrigated conditions following the Global Agro-Ecological Zoning methodology developed by the International Institute for Applied Systems Analysis (IIASA) and FAO (Fischer *et al*., 2021) and using the latest available GAEZ assessment (FAO and IIASA, 2025a). GAEZ data and methods are described in the next section and presented in more detail in the **Annex**.

Using IPCC climate scenarios, GAEZ was also used to assess the impact of climate change on land suitability, crop water demand and crop production potential for selected crop groups. ■

BOX 2 SOIL AND TERRAIN FACTORS CONSIDERED IN GLOBAL AGRO-ECOLOGICAL ZONING

- Nutrient availability
- Soil nutrient retention capacity
- Soil depth
- Oxygen availability
- Salinity and sodicity levels
- Calcium carbonate and gypsum levels
- Soil workability
- Slope

SUITABILITY ANALYSIS

Crop production is the result of a combination of climatic, edaphic, biotic, physiographic and socioeconomic factors. For a given location, the suitability of land varies based on crop type and management practices. Globally available data on climate, soil and terrain make it possible to assess the suitability of land for many crops (Fischer *et al*., 2021).

The GAEZ methodology matches available global georeferenced datasets on agroclimatic, soil and terrain conditions with specific crop requirements to determine suitable agricultural land-use options and model the agronomically attainable yield for the production of 52 crops.[f] These factors are used to evaluate the suitability of land and the production potential of individual crops under various input and management conditions; estimate yield gaps by comparing actual yield with attainable yield; and identify hotspots where more productive land use is possible.

Suitability analysis is at the core of the GAEZ methodology, providing information on the potential and limitations of land for each type of crop. GAEZ considers seven suitability classes, ranging from highly suitable to unsuitable. When land is highly suitable for a given crop, and considering optimal management conditions, it is expected that the land can produce more than 80 percent of the attainable yield. This capacity decreases progressively until it reaches zero for unsuitable land.

Land suitability refers to the potential of land to support productive agriculture and is influenced by two main variables: agroclimatic and agroedaphic factors. Agroclimatic factors include temperature, precipitation, solar radiation and the length of the growing period, all of which influence crop growth and development. Agroedaphic factors relate to soil and terrain characteristics, which can affect root development, water availability, nutrient supply and overall soil productivity (see Box 2). Understanding how crop requirements align with both agroclimatic and agroedaphic factors, combined with the application of appropriate management practices, is essential for enhancing agricultural production and land productivity.

Land suitability analysis provides the biophysical assessment of the potential to enhance productivity. To consider competing land uses and ecological/sustainability constraints, integrated land-use planning (ILUP) is needed at different levels of decision-making to address challenges and competing demands (FAO, forthcoming). ■

f Attainable yield in the context of GAEZ refers to the maximum yield that can be achieved under specific agroecological conditions, combining agroclimatic potential yields with soil and terrain evaluations. It takes account of biophysical limitations such as temperature, moisture availability, soil type and slope, as well as specified levels of agronomic inputs and management practices. Attainable yield is distinct from potential yield as it integrates realistic constraints of soil and terrain, providing a more practical estimate of productivity for a given crop under defined conditions. For further details, see: GAEZ 4 FAQ

TABLE 8 SUITABILITY CLASSES CONSIDERED IN THE GLOBAL AGRO-ECOLOGICAL ZONING ANALYSIS

Category of land suitability	GAEZ suitability class	Attainable percentage of maximum yield	Farm economics
Prime land	VS – very suitable	80–100	Prime land offering best conditions for economic crop production
Good land	S – suitable	60–80	Good land for economic crop production
	MS – moderately suitable	40–60	Moderate land with substantial climate and/or soil/terrain constraints requiring high product prices for profitability
Marginal land	mS – marginally suitable	20–40	Commercial production not viable; land could be used for production when no other land is available
	vmS – very marginally suitable	<20	Economic production not feasible
Unsuitable land	NS – not suitable	0	Production not possible

SOURCE: Fischer, G., Nachtergaele, F.O., van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D. & Tramberend, S. 2021. *Global Agro-Ecological Zones (GAEZ v4) – Model Documentation*. Rome, FAO. https://doi.org/10.4060/cb4744en

LAND POTENTIAL FOR CULTIVATION: UNEVEN GEOGRAPHICAL DISTRIBUTION

Leveraging GAEZ v5 data (FAO and IIASA, 2025a), the suitability and spatial distribution of land for cultivation was evaluated. The analysis focused on rainfed potential, through the evaluation of agroclimatically suitable areas for the 52 crops. The methodology aggregated data across all crops to identify the maximum cultivable extent for each geographic unit, land cover/land use type and management intensity level – specifically low-input and high-input systems (see Box 3). The high-input system represents theoretical scenarios useful to explore and contrast outcomes under different management conditions. GAEZ v5 contains information for the historical scenario 2001–2020 as well as for future climatic scenarios as defined by the IPCC. The analysis further classifies GAEZ crop-specific categories of land suitability into prime land, good land, marginal land and unsuitable land (see Table 8). The land cover classification of GAEZ v5 (FAO and IIASA, 2025b) integrates a cropland agreement map obtained from multiple high-resolution products (Tubiello *et al*., 2023a) with FAOSTAT statistics. Finally, all the areas listed in the World Database on Protected Areas, totalling approximately 1.8 billion ha (UNEP-WCMC and IUCN, 2022), of which about half are protected forest, were excluded from the analysis.

It should be emphasized that the assessment of land suitability for cultivation is based only on the characteristics of the land and does not consider existing land use and whether any conversion to cropland is acceptable. For instance, the expansion of agriculture into existing forests is in most cases not a strategic option.

The extent of prime land – land with the highest suitability for cropping – varies significantly depending on the management level. Globally, GAEZ estimates that approximately 800 Mha of land can be considered prime land under a low-input scenario (see Figure 15). This area doubles to over 1 600 Mha under an advanced management scenario, an area larger than the current extent of cropland (FAO, 2025a). Approximately one-fifth of current cropland is classified as prime land under a low-input scenario, and one-third under a high-input scenario. In terms of land cover/land use, prime land is distributed roughly equally between croplands, grasslands and shrublands, and tree-covered areas.

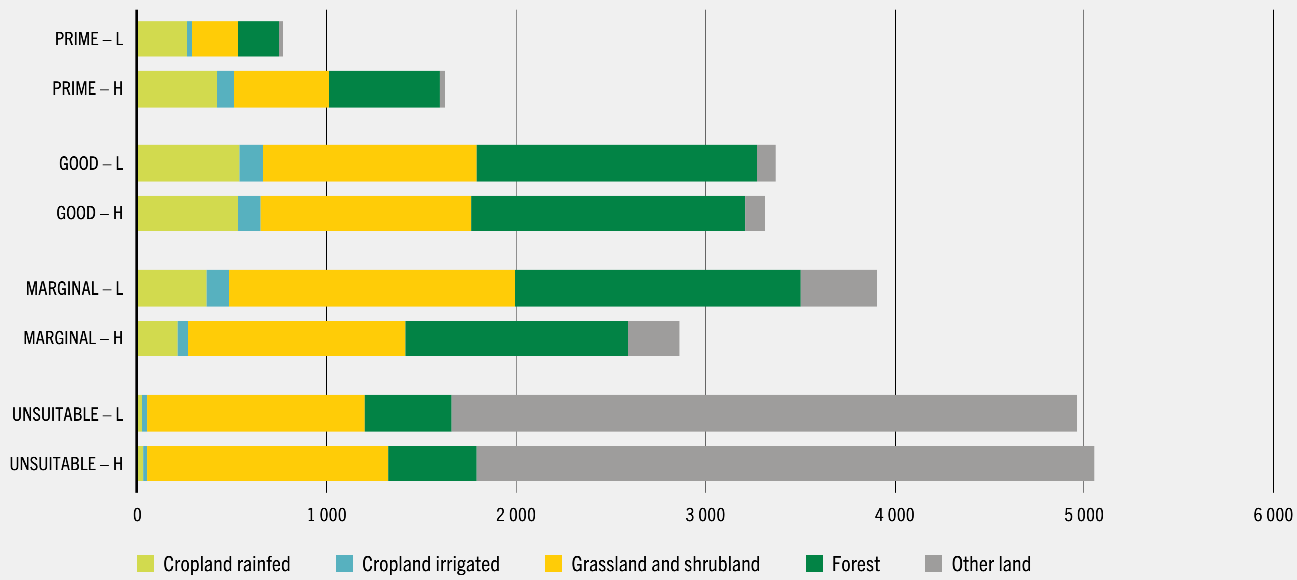
The spatial extent of good land remains stable at about 3 300 Mha across both input scenarios,

BOX 3 LEVELS OF INPUT AND MANAGEMENT CONSIDERED IN GLOBAL AGRO-ECOLOGICAL ZONING

Low-level input/limited management. Under the limited management assumption, the farming system is largely subsistence-based and not necessarily market-oriented. Production is based mainly on the use of local cultivars and labour-intensive techniques. It entails no application of fertilizers, no use of chemicals for pest and disease control, and minimum conservation measures.

High-level input/advanced management. Under the advanced management assumption, the farming system is mainly market-oriented; producing for the market is a management objective. Production is based on improved varieties and mechanization with low labour intensity. It uses optimum applications of nutrients and applies chemical pest, disease and weed control.

FIGURE 15 GLOBAL DISTRIBUTION OF LAND SUITABLE FOR CULTIVATION BY LAND COVER CLASS, UNDER LOW-INPUT (L) AND HIGH-INPUT (H) MANAGEMENT SCENARIOS, AVERAGE 2001–2020



NOTE: Protected areas are excluded.

SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

https://doi.org/10.4060/cd7488en-fig15

suggesting lower sensitivity to management intensification. Good land comprises 45 percent of cropland, 40 percent of land used for forest, and nearly 30 percent of land under grassland and shrubland.

About one-third of cropland is classified as marginal under low-input conditions. Implementing advanced management practices would reduce this proportion by nearly half – an inverse trend compared with the trend observed for prime land.

Figure 15 also shows the share of cropland that is irrigated and its distribution across suitability classes. Irrigation removes one of the most important suitability constraints by ensuring adequate soil moisture, making it possible to compensate for erratic or insufficient precipitation and achieve higher production. Over half of the 300 Mha of irrigated cropland are found in prime and good land under the low-input scenario. This proportion rises to over 70 percent under advanced management.

The analysis of the regional distribution of suitable land (see Figure 16) shows considerable differences between regions, including in terms of potential for low-input and high-input management scenarios. The Americas boast the largest area of prime land, spanning nearly 350 Mha in the low-input scenario and more than double that figure in the high-input management scenario. Europe follows with approximately 250 Mha or 32 percent of global prime land in the low-input scenario. In contrast with the Americas, this value grows only slightly under advanced management, indicating that suitable agroclimatic and agroedaphic conditions are prevalent in this region. Asia has approximately 120 Mha of prime land in the low-input scenario and more than double in the high-input scenario. The largest gain in prime land across the two scenarios is observed in Africa, where improved management would determine a sevenfold growth in the extent of prime land, increasing from 55 Mha (low-input) to 360 Mha (high-input). This is especially important given that less than 5 percent of the total land area in Africa has the most favourable conditions for cultivation. Oceania ranks last with only 6 Mha of prime land under low-input conditions, increasing to 14 Mha with advanced management practices.

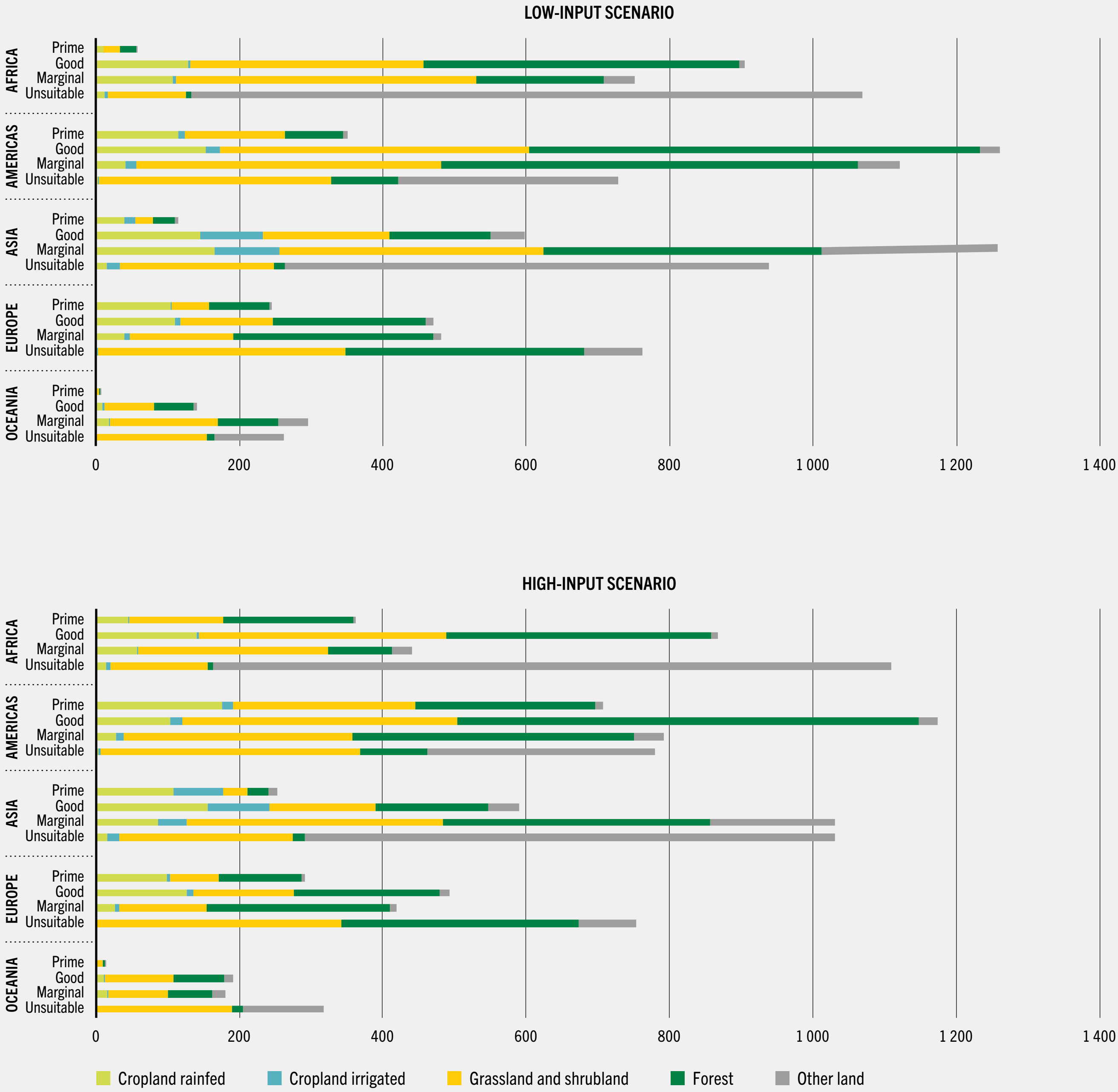
Prime land is used differently across the regions. Under limited management conditions, Africa has less than 20 percent of its prime land under cropland, corresponding to 10 Mha, while a comparable extent of prime land is found under tree-covered areas as well as grassland and shrubland (often coinciding with land used for pastures), amounting to 22 Mha. In Asia and Europe, prime land under cropland accounts for the largest shares of regional prime land (48 and 43 percent, respectively). Both the Americas and Oceania have the largest extents of prime land under grassland and shrubland, with shares of regional prime land of 40 and 60 percent, respectively.

When considering the geographical distribution of land with good suitability for cultivation, the Americas and Africa rank highest with 1 200 Mha and 900 Mha, respectively, under low-input management and comparable extents under advanced management conditions. With a lower extent (approximately 600 Mha of land with good suitability under both management levels), Asia has over 40 percent of its good land used for cropland, while Africa and the Americas both have only 14 percent. Both these latter regions have large shares of their good land under forest and under grassland and shrubland, which significantly restricts opportunities for expansion. The expansion of agriculture into forest is not an option. This report proposes alternative areas for expansion to enhance sustainable food production and, at the same time, safeguard forest and protected areas. Europe has approximately 500 Mha of good land, of which about one-quarter is used for cropland under the two management scenarios. Finally, Oceania has 140 Mha and 190 Mha of good land under low-input and high-input management levels, respectively. Less than 10 percent of this good land is cultivated, while half is under grassland and shrubland.

Asia and the Americas have the greatest extent of marginally suitable land, with 1 200 Mha and 1 100 Mha, respectively, under low-input management. These areas decrease by 16 percent in Asia and by 30 percent in the Americas under more advanced management practices. Africa follows with nearly 800 Mha of marginal land, which is reduced by 43 percent under high-input conditions. Europe has approximately 500 Mha of marginal land under low-input management, decreasing to 420 Mha with advanced practices. In Oceania, marginal lands amount to 300 Mha under low-input scenarios, declining by 40 percent under high-input management.

In theory, a very small share of marginally suitable land should be used for crops. However, under low-input conditions, both Africa and Asia have more than two-fifths of their current cropland on land with marginal suitability; this »

FIGURE 16 REGIONAL DISTRIBUTION OF LAND BY SUITABILITY FOR PREVALENT LAND COVER/LAND USE UNDER LOW-INPUT AND HIGH-INPUT MANAGEMENT SCENARIOS, AVERAGE 2001–2020



NOTE: Protected areas are excluded.

SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

https://doi.org/10.4060/cd7488en-fig16

BOX 4 UNLOCKING THE POTENTIAL OF MARGINAL LANDS

Since its initial conceptualization (Ricardo, 1817), the definition of marginal land has remained a subject of debate. Existing definitions vary significantly depending on application purposes and contextual frameworks. Against a backdrop of escalating global food demand driven by population growth and dietary transitions towards resource-intensive diets, the potential of marginal lands to enhance food security has garnered significant global attention.

A growing body of research has investigated marginality through agricultural or arable land-use perspectives. While marginality emerges from multifactorial interactions, studies consistently identify two interlinked underlying determinants: biophysical and socioeconomic factors (Csikós and Tóth, 2023). Marginal land therefore refers to land with low productivity due to biophysical conditions such as rugged terrain, poor soil quality and extreme weather conditions (including scattered and low precipitation), as well as to productive land constrained by socioeconomic factors such as human-induced land degradation, market price instability, land tenure conditions and limited access to markets and infrastructure, which render it incapable of cost-effective production under given conditions.

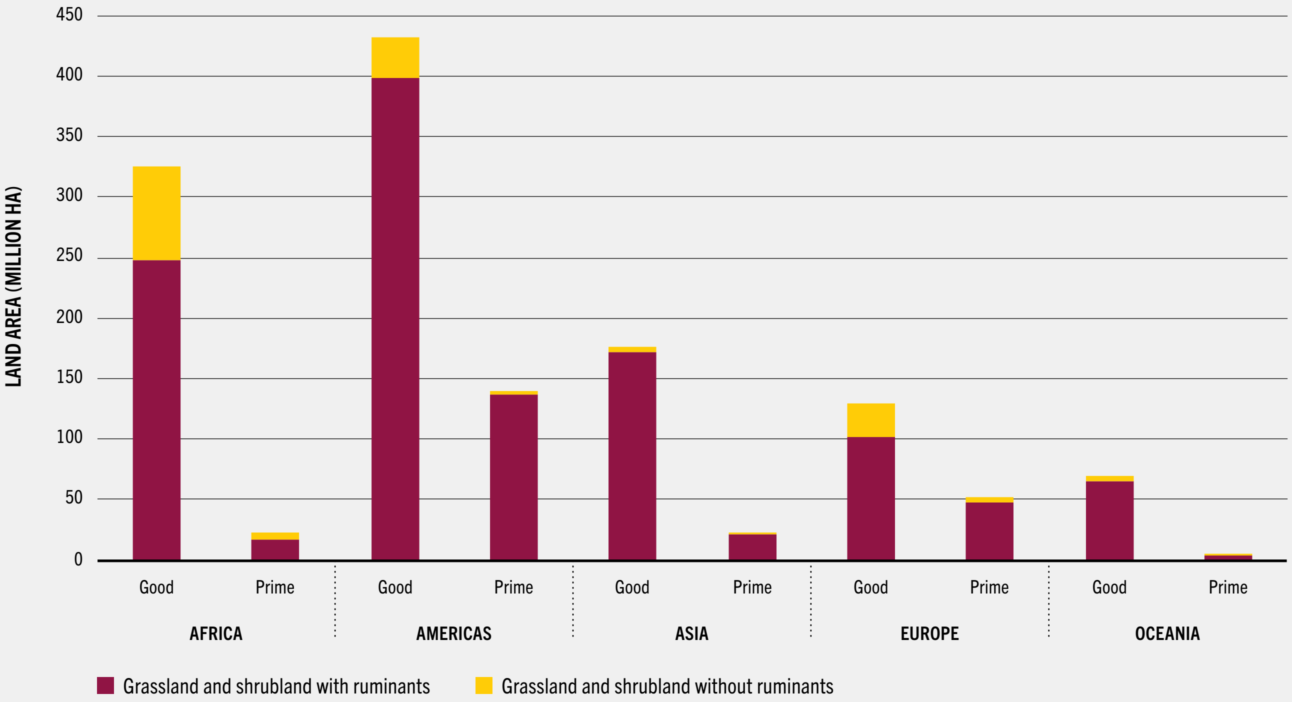
The literature offers a variety of figures on the extent and prevalence of marginal lands, as different studies employ different methods, assumptions and criteria to estimate the extent of global marginal lands. The Global Agro-Ecological Zoning (GAEZ) methodology used in this report combines climate characteristics and soil and terrain qualities with crop requirements, and estimates the suitability in terms of attainable yield given the different levels of technology and management. It therefore focuses more specifically on biophysical factors.

It is important to note that the boundary between marginal and productive land is not static. Inappropriate land-use activities and a changing climate may lead to the degradation of productive land into marginal land, while – with appropriate technology and land management practices – marginal land can be transformed into productive agricultural land (Csikós and Tóth, 2023).

Given the varying characteristics of marginal lands in different regions and the diversity of factors affecting land marginality, the management of marginal lands should be adapted to local conditions. Financial and policy instruments, including flexible policies and practices, need to be developed to achieve the sustainable management of marginal lands. The land suitability and yield gap analyses presented in this report provide information about opportunities to enhance the productivity of marginal lands. Examples of coping strategies for marginal lands are presented in the table.

Climatic zones	Coping strategies	Financial input
Arid and semi-arid zones	Soil improvement, development and modernization of irrigation and drainage systems, water harvesting, use of drought-resistant crops and improved varieties	High initial investments
Humid tropics	Planting of acid-tolerant crops, crop rotation, conservation tillage, intercropping	Relatively low costs
Temperate and semi-humid regions	Reduction of soil disturbance, use of crop rotation, soil and water conservation, ecological restoration	Relatively low costs
Highlands	Terracing, soil and water conservation, ecological restoration	Substantial initial investments and policy support
Mediterranean zones	Conservation tillage, planting of drought-resistant varieties, improvement of irrigation and drainage facilities	Moderate costs
Boreal and cold zones	Planting of cold-resistant varieties, rangeland management	Moderate costs

FIGURE 17 REGIONAL DISTRIBUTION OF PRIME AND GOOD LAND IN GRASSLAND AND SHRUBLAND UNDER LOW-INPUT MANAGEMENT AND RAINFED CONDITIONS, WITH AND WITHOUT GRAZING ANIMALS, 2015



SOURCES: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en; FAO. 2025. Gridded Livestock of the World: Gridded livestock density (Global - 2015 - 10 km) - GLW4. [Accessed on 13 March 2025]. https://data.apps.fao.org/catalog//iso/15f8c56c-5499-45d5-bd89-59ef6c026704. Licence: CC-BY-4.0; Gilbert, M., Nicolas, G., Cinardi, G., Van Boeckel, T.P., Vanwambeke, S.O., Wint, G.R.W. & Robinson, T.P. 2018. Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data*, 5(1): 180227. https://doi.org/10.1038/sdata.2018.227; FAO. 2022. Global Livestock Environmental Assessment Model (GLEAM) 3 Dashboard. Livestock emission data at a glance. [Accessed on 13 March 2025]. https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig17

» proportion surpasses 60 percent in Oceania. The Americas and Europe have smaller shares of cropland with marginal suitability – less than 20 percent in both cases. While cultivation is indeed the least frequent use of marginal land across all regions, the extent of cropland in marginal areas indicates a geographical imbalance between demand for and availability of land for cultivation, in particular in Africa and parts of Asia, forcing farmers to cultivate marginal lands. It is also worth noting that while the natural endowment appears to be a limiting factor to cultivation in these regions, data also suggest important opportunities for attaining higher productivity with improved land management. In Africa, significant differences are observed between the two levels of management, with marginal land under cropland decreasing from 120 Mha under low-input conditions to half of that figure under improved management practices. Box 4 discusses options for unlocking the potential of marginal lands.

Looking strictly at land resources, and under the (unlikely) hypothesis that neither productivity levels nor per capita demand change, it would be possible to produce enough food for a projected global population of 9.7 billion in 2050, peaking at 10.3 billion in the mid-2080s. This would mean that cropland would need to increase from its current 1.6 billion ha to 1.9 billion ha in 2050 and 2.1 billion ha in the mid-2080s, which is substantially less than the 4 billion ha of prime and good land currently available. However, this global figure has limited meaning. It does not consider the large variations between regions and between countries; it takes into account neither competition with other uses (including urbanization), nor the degradation of currently used land. Furthermore, whatever increase in cropland occurs, it will be at the expense of other land uses and will further increase the already large environmental footprint of agriculture. Ignoring the competition with other environmental services and the need to address the trade-offs would result in further degradation of the resources, in particular biodiversity and the regulating functions of ecosystems (Fischer *et al*, 2011).

Preserving forest and grassland ecosystems is crucial to address the challenges of climate change and biological diversity. These ecosystems are essential to maintaining global carbon balance (IPCC, 2022) and providing critical products and services (e.g. non-timber forest products, biodiversity, pollination, water quality) that support adaptation and resilience (FAO, 2020). Although prime and good land amount globally to more than 4 billion ha, the opportunities for expansion are limited, as large shares of this land are used by forest or for pastures (see Figure 17). Globally, 160 Mha of primarily good land under grasslands are estimated to be potentially available for cultivation or for mixed livestock–cropping systems. About half of this land is in Africa, with 40 Mha in the Americas and 30 Mha in Europe. Grasslands and shrublands already sustain the livelihoods of millions of people who rely on these ecosystems for food, fuel and fibre, as well as cultural services (Bardgett *et al*., 2021). For instance, the Sahel Great Green Wall initiative aims to restore 100 Mha of degraded land under agrosilvopastoral systems by 2030. More than 50 Mha – or 10 percent of the total area of interest of this regional effort – are under grazed land (Sacande *et al*., 2022). ■

YIELD GAP AND OPPORTUNITIES TO INCREASE PRODUCTION ON EXISTING RAINFED LAND

Yield gap across main crop groups and selected crops

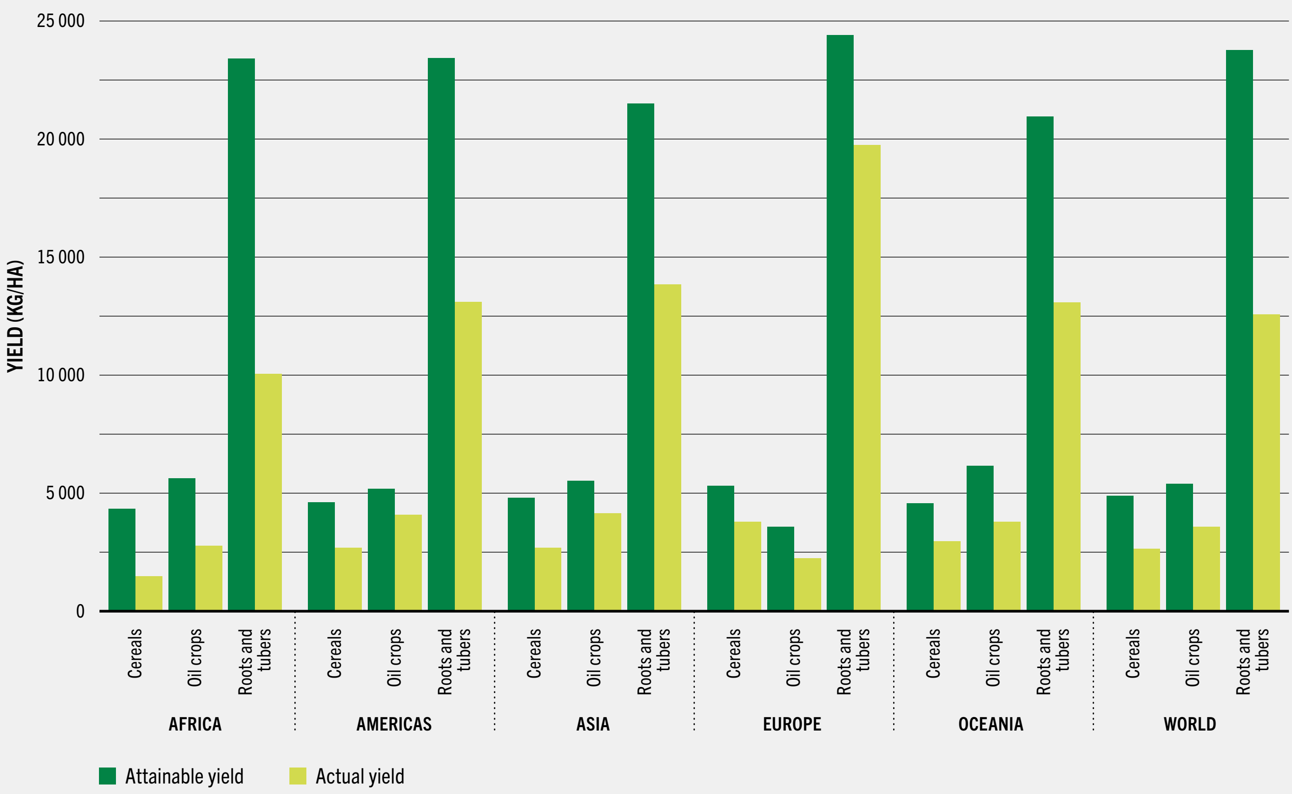
Yield gaps arise from a series of limitations faced by producers, including technical constraints such as limited access to seeds, plant nutrients and pest control capacities, as well as technologies such as mechanization, storage facilities or irrigation. Furthermore, poor access to knowledge and finance, as well as market inefficiencies and policy gaps, play an important role in determining the yield of specific crops.

For each of the 52 crops analysed, GAEZ provides estimates of the attainable yield for given local conditions. GAEZ v5 was used to assess attainable yields and compare them with country-level yield data obtained from FAOSTAT (FAO, 2025b). This analysis was conducted for three crop groups (cereals, roots and tubers, and oil crops) and selected crops, comparing GAEZ v5 data for the historical scenario 2001–2020 with FAOSTAT data averaged over the same period. For a description of the detailed methodology, see the **Annex**.

At global level, cereal yields averaged slightly above 50 percent of the estimated attainable yields, corresponding to a yield gap of approximately 2 200 kg/ha in absolute terms. In contrast, oil crops performed better, with actual yields corresponding to over 65 percent of their attainable levels and yield gaps of 1 800 kg/ha. Roots and tubers showed actual yields averaging approximately half of the attainable yields, with a substantial yield gap of more than 12 000 kg/ha.

Important variations in cereal production performance exist between countries and between regions (see Figure 18). Africa exhibits the largest gap between attainable and actual yields for cereals, pointing to significant opportunities for improvement: on average, cereal yields in Africa are only one-third of their attainable level,

FIGURE 18 **ATTAINABLE AND ACTUAL YIELDS, GLOBAL AND REGIONAL RESULTS FOR CEREALS, OIL CROPS, AND ROOTS AND TUBERS, AVERAGE 2001–2020**



SOURCES: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en; FAO. 2025. FAOSTAT: Crops and livestock products. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0

https://doi.org/10.4060/cd7488en-fig18

resulting in a gap of approximately 2 800 kg/ha. The Americas and Asia show yield gaps for cereals close to the global average (54 percent). Europe and Oceania have the smallest gaps between attainable and actual yields, reflecting better performance in cereal production: in Europe, average yields are almost three-quarters of their attainable level, with a gap of 1 500 kg/ha, while in Oceania, actual cereal yields are about two-thirds of the attainable level, amounting to a yield gap of 1 600 kg/ha in absolute terms.

For oil crops, Africa has the greatest opportunity for improvement compared with the other regions. Actual yields from oil crops in this region are about half of the attainable level, with a yield gap of 2 900 kg/ha. The Americas and Asia show good performance levels, with actual yields reaching more than three-quarters of the attainable level and a yield gap of about 1 100 kg/ha in both regions. Europe and Oceania record similar outcomes, with actual oil crop yields ranging between 62 and 63 percent of their attainable level and yield gaps of 1 300 kg/ha and 2 400 kg/ha, respectively.

Global yields from roots and tubers average about 50 percent of their potential, with variations across regions, ranging from 43 percent in Africa to 56 percent in the Americas and 62–65 percent in Asia and Oceania. Europe achieves more than 80 percent of its attainable level for this crop group, with a yield gap of 5 000 kg/ha.

»

RWANDA
Manure is collected and applied to fields as mulch to enhance water retention and prevent dispersion and erosion.
© FAO/Marco Longari

» Figure 19 shows the level of severity of the yield gap for maize, rice and wheat, by country and across regions. The analysis identifies five levels of severity: limited (0–20 percent); moderate (20–40 percent); significant (40–60 percent); severe (60–80 percent); and very severe (80–100 percent). Maize, with the broadest geographical distribution, was analysed in 159 countries. Wheat data covered 124 countries, while rice, due to more specific cultivation requirements, was analysed for 118 countries.

Severe and very severe yield gaps (>60 percent) are common in maize-producing countries. Most African nations face significant yield gaps, with none achieving the best performance category (<20 percent gap). By contrast, Asian and European countries generally exhibit smaller yield gaps for maize.

Wheat also presents widespread large yield gaps, with 50 countries across regions experiencing severe gaps (60–80 percent), signalling that there is strong potential for improvement in this crop. In contrast with maize, also African countries exhibit smaller yield gaps for wheat.

Rice yield gaps exhibit a distinct pattern compared with maize and wheat. Approximately half of all rice-producing countries fall into the limited yield gap category (0–20 percent), showing excellent performance levels. A study by Gerber *et al*. (2024) confirms that rice yield gaps have narrowed globally over the past decades, with more than 84 percent of rice areas now approaching attainable yields.

Reducing yield gaps

The gap between actual and attainable yields reflects a combination of environmental, socioeconomic and institutional factors. In most cases, productivity is driven by markets, availability and access to finance, inputs, technology and knowledge, which impact farmers' capacity to efficiently address the main constraints to production.

The availability of soil nutrients is the single most important soil and terrain factor limiting yield, in both prime and good lands and in marginal lands across the regions; it is especially relevant in Africa (see Figure 20). This issue can be addressed through improved soil nutrient management and sustainable mechanization. Associated with limited availability of nutrients is the capacity of soils to retain nutrients, a quality that varies according to the soil's characteristics. In some parts of tropical regions, soils have poor retention capacity, further complicating nutrient management.

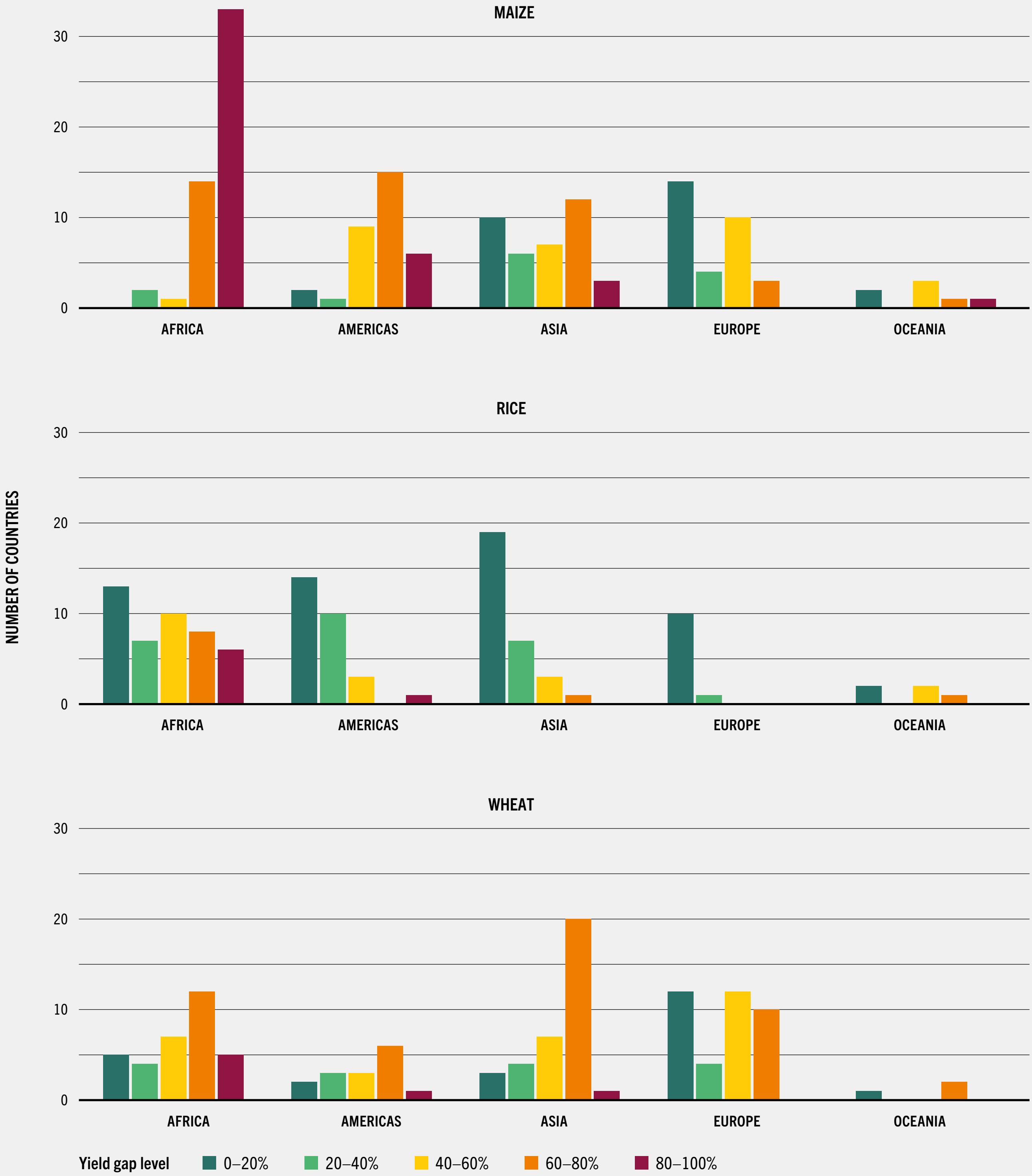
Addressing soil and terrain constraints requires specific solutions. For example, excessive sloping can be addressed by terracing; poor drainage can be improved with artificial drains; and excess of salt can be resolved either through drainage and leaching or through selection of salt-tolerant crops. The feasibility of these solutions will depend on their cost-effectiveness and on the availability of the finance, technologies and knowledge that they require. **Chapter 4** gives a detailed presentation of the technological options for increasing yields and reducing the yield gap.

Chapter 5 discusses the enabling environment needed to place farmers in a position to increase productivity and enhance capacity for the planning and management of land resources. Integrated land-use planning involves balancing competing demands for land among different sectors of the economy. FAO is in the process of publishing new ILUP guidelines (FAO, forthcoming). As part of a nine-step process, ILUP includes land suitability analysis, complemented by the selection of sustainable land-use options. A multicriteria analysis supports the decision on the optimum land-use option(s) that enhance production, promote sustainability and assist in achieving multiple benefits with minimum impact. Stakeholder consultation is central to the ILUP process. ■

THE ROLE OF WATER IN FUTURE AGRICULTURAL INTENSIFICATION

Irrigation has always been a way of enhancing the suitability of land for agricultural production. It can take place in an arid environment, where agriculture is otherwise not possible, or it may be practised in more favourable environments, either to protect production from climate irregularities »

FIGURE 19 YIELD GAPS FOR MAIZE, RICE AND WHEAT BY SEVERITY LEVEL, AVERAGE 2001–2020

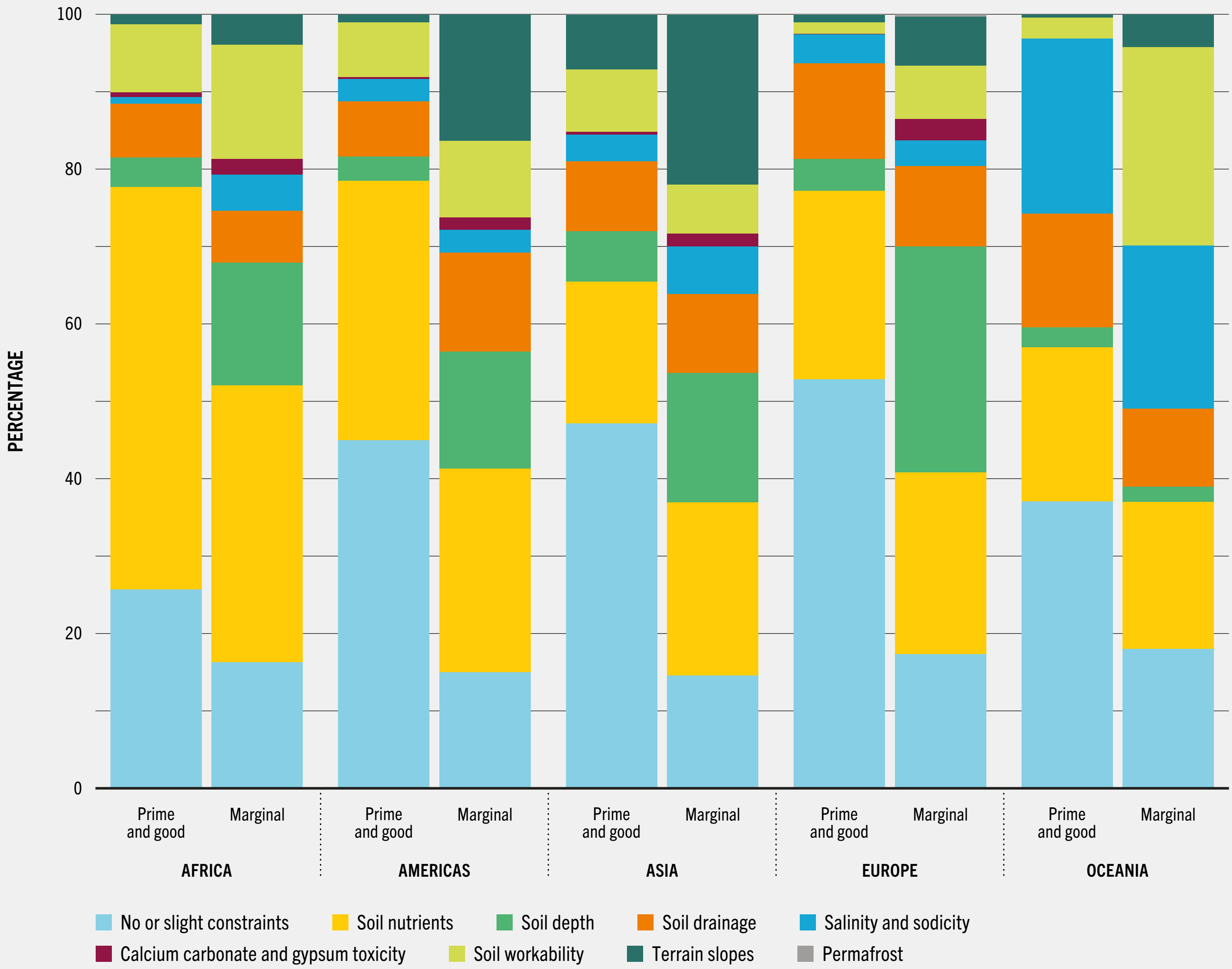


NOTE: Level of severity of yield gap: limited (0–20 percent); moderate (20–40 percent); significant (40–60 percent); severe (60–80 percent); and very severe (80–100 percent).

SOURCES: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en; FAO. 2025. FAOSTAT: Crops and livestock products. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig19

FIGURE 20 **MAIN SOIL AND TERRAIN CONSTRAINTS IN CONDITIONS OF LOW-INPUT MANAGEMENT IN CURRENT CROPLAND BY REGION AND SUITABILITY CLASS**



SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

https://doi.org/10.4060/cd7488en-fig20

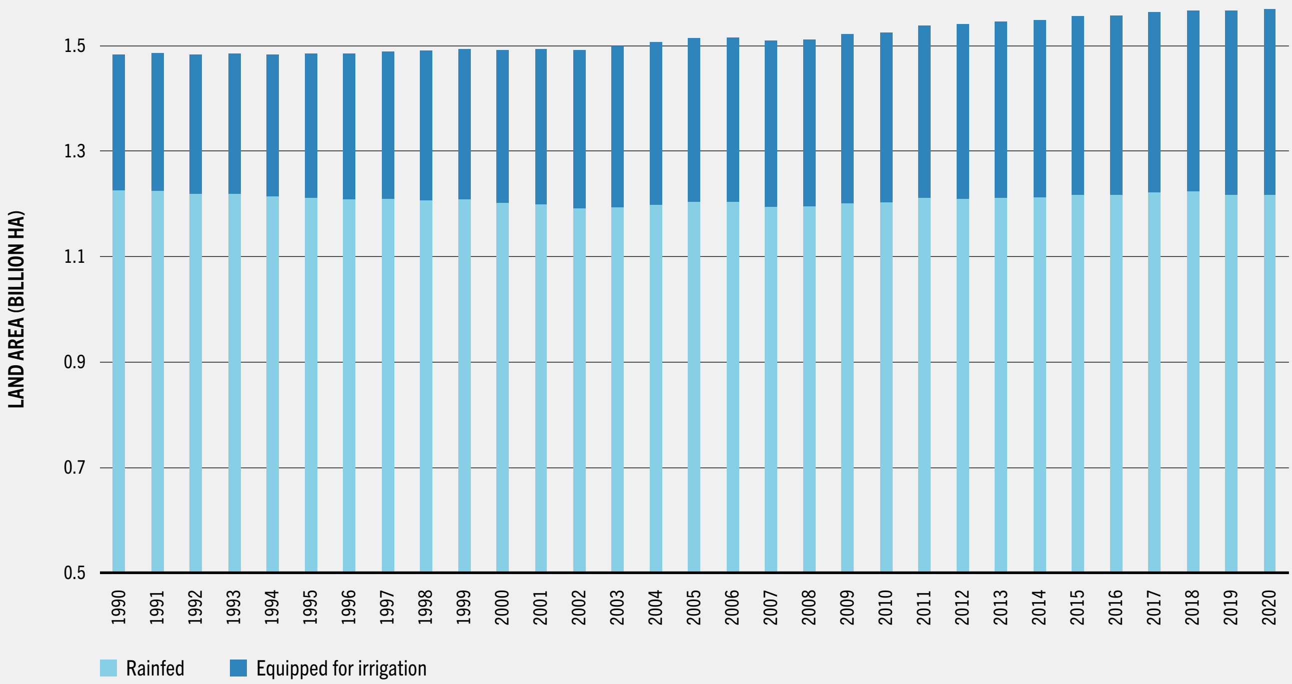
» or to increase cropping intensity.[g] Irrigation increases the suitability of most land where water, and therefore climate – in particular the rainfall regime – is the main constraint to production.

Over the years, the push for greater productivity has resulted in increased access to irrigation (see Figure 21), making agriculture by far the main water use sector and pushing the limits of sustainability in an increasing number of regions.

g Cropping intensity is the harvested area expressed as a percentage of the arable area. Cropping intensity can be higher than 100 percent when more than one crop is grown on the same land over an agricultural year.

The possibility for further expansion of irrigated agriculture depends largely on the levels of water stress. SDG Indicator 6.4.2 measures water stress as the ratio of total freshwater withdrawn to the total renewable freshwater resources within a specific region, after considering environmental flow requirements. This metric quantifies the degree to which water use impacts the sustainable replenishment of freshwater resources in a given area. Values below 25 percent can be considered safe under any circumstances (no stress). Beyond the 25 percent threshold of water stress, four classes have been established for SDG Indicator 6.4.2 to indicate

FIGURE 21 **TRENDS IN LAND UNDER IRRIGATION AND RAINFED CROPPING, 1990–2020**



NOTE: The land equipped for irrigation is used as a proxy for land under irrigation due to the lack of global statistics on areas actually irrigated.
SOURCE: FAO. 2025. FAOSTAT: Land Use. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd7488en-fig21

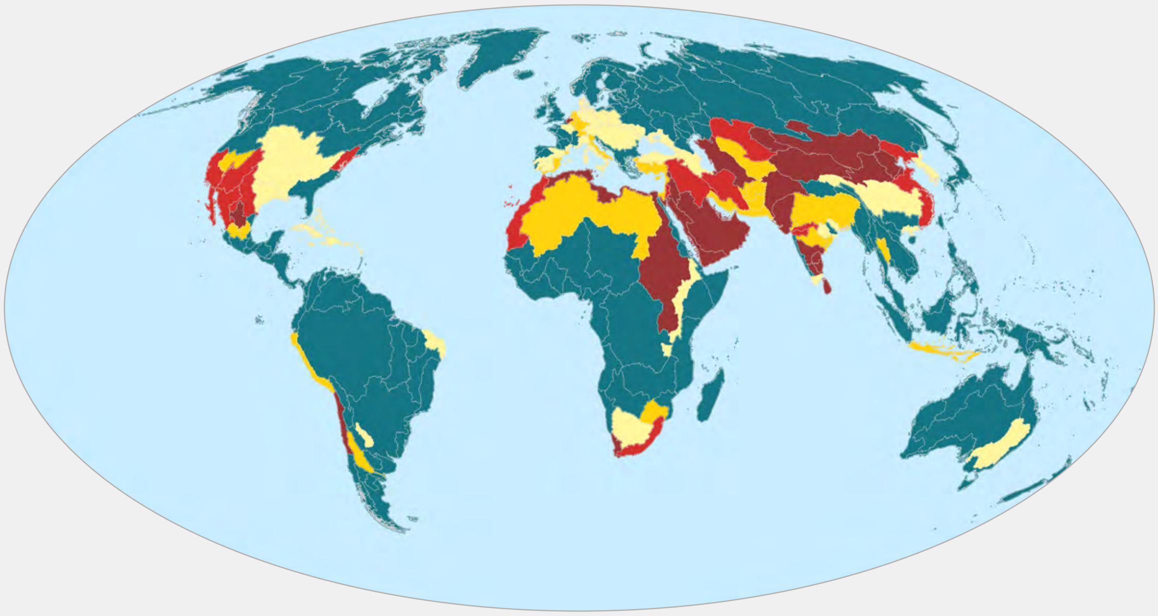
different levels of stress severity (low, medium, high and critical).

In this context, regions with lower water stress have more water available for the expansion of irrigated areas, while regions with high water stress find themselves in a situation of competition within and across sectors. Figure 22 illustrates the findings from the 2024 status report of SDG Indicator 6.4.2 (FAO and UN-Water, 2024).

The map may be interpreted as showing that there are still many areas where water availability is not an issue. However, these are mostly areas with abundant precipitation and little need for irrigation, while in the subtropical areas on both sides of the Equator, where precipitation is scarce, there are very few areas with low levels of water stress. Areas where existing yields can be boosted by applying water in agriculture are primarily located in sub-Saharan Africa, where yields are generally low and water is available, and to a lesser extent in Latin America. In most of Asia, irrigation is already practised on a large scale.

The physical dimension of water stress illustrated by SDG Indicator 6.4.2 represents just one dimension of water scarcity. Other dimensions of water scarcity (FAO, 2012) include the economic dimension, by which water may be abundant, but financial resources are not available to develop the infrastructure needed to take advantage of it. Institutional and organizational scarcity, or scarcity of accountability, refer to the lack of capacity of institutions to respond to the need to access water in the right place at the right time. ■

FIGURE 22 **LEVEL OF WATER STRESS BY MAJOR RIVER BASIN, 2018–2021**



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

NOTE: Numbers in brackets indicate the ratio of total freshwater withdrawn to the total renewable freshwater resources.

SOURCE: FAO & UN-Water. 2024. Progress on the level of water stress – Mid-term status of SDG Indicator 6.4.2 and acceleration needs, with special focus on food security – 2024. Rome, FAO. https://doi.org/10.4060/cd2179en

ASSESSING THE IMPACTS OF CLIMATE CHANGE ON LAND AND WATER REQUIREMENTS

Impact on land suitability for cultivation

Studies of global land suitability for agriculture suggest that climate change will increase the area suitable for agriculture in the northern high latitudes, while tropical regions will experience a reduction in the area suitable for agriculture (Ramankutty *et al*., 2002; Zabel, Putzenlechner and Mauser, 2014; Olsson *et al*., 2019).

Of particular concern are coastal areas, including major deltas that are often intensely cultivated. These areas frequently face challenges such as coastal flooding, cyclones, storm surges, waterlogging and seawater intrusion (Habiba and Abedin, 2024). All these challenges are exacerbated by climate change and lead to degradation of soil productivity, affecting agricultural productivity.

In this report, GAEZ v5 estimates of suitable land for four selected crops during the historical period 2001–2020 were compared with projected land suitability derived from an ensemble of five climate change models. The analysis included two Shared Socioeconomic Pathways (SSPs), each associated with specific greenhouse gas

TABLE 9 EXTENT OF SUITABLE AREA UNDER HISTORICAL CLIMATE SCENARIO (2001–2020) AND NET VARIATIONS FOR FUTURE CLIMATE SCENARIOS (2081–2100): SSP 2.6 (LOW EMISSIONS) AND SSP 8.5 (HIGH EMISSIONS)

Region	Cassava			Maize		
	Historical (2001–2020)	Future (2081–2100)		Historical (2001–2020)	Future (2081–2100)	
	Extent (million ha)	SSP 2.6 Variation (%)	SSP 8.5 Variation (%)	Extent (million ha)	SSP 2.6 Variation (%)	SSP 8.5 Variation (%)
Africa	106.3	10	12	136.0	6	14
Americas	114.8	17	43	239.4	16	20
Asia	218.1	4	9	344.3	5	9
Europe	0.3	77	2 419	184.3	21	18
Oceania	1.5	58	212	1.9	132	191
WORLD	**441.0**	**9.1**	**21.1**	**905.8**	**11.3**	**14.7**

Region	Soybean			Wheat		
	Historical (2001–2020)	Future (2081–2100)		Historical (2001–2020)	Future (2081–2100)	
	Extent (million ha)	SSP 2.6 Variation (%)	SSP 8.5 Variation (%)	Extent (million ha)	SSP 2.6 Variation (%)	SSP 8.5 Variation (%)
Africa	127.6	9	12	57.2	–11	–57
Americas	219.7	9	10	248.5	2	–6
Asia	271.1	3	–1	260.0	–1	–22
Europe	84.7	43	28	224.9	7	7
Oceania	1.8	120	156	9.3	138	87
WORLD	**704.9**	**10.9**	**8.6**	**799.9**	**3.2**	**–10.2**

NOTES: SSP – Shared Socioeconomic Pathway. Totals include suitable land with prime and good suitability for each crop under rainfed conditions.

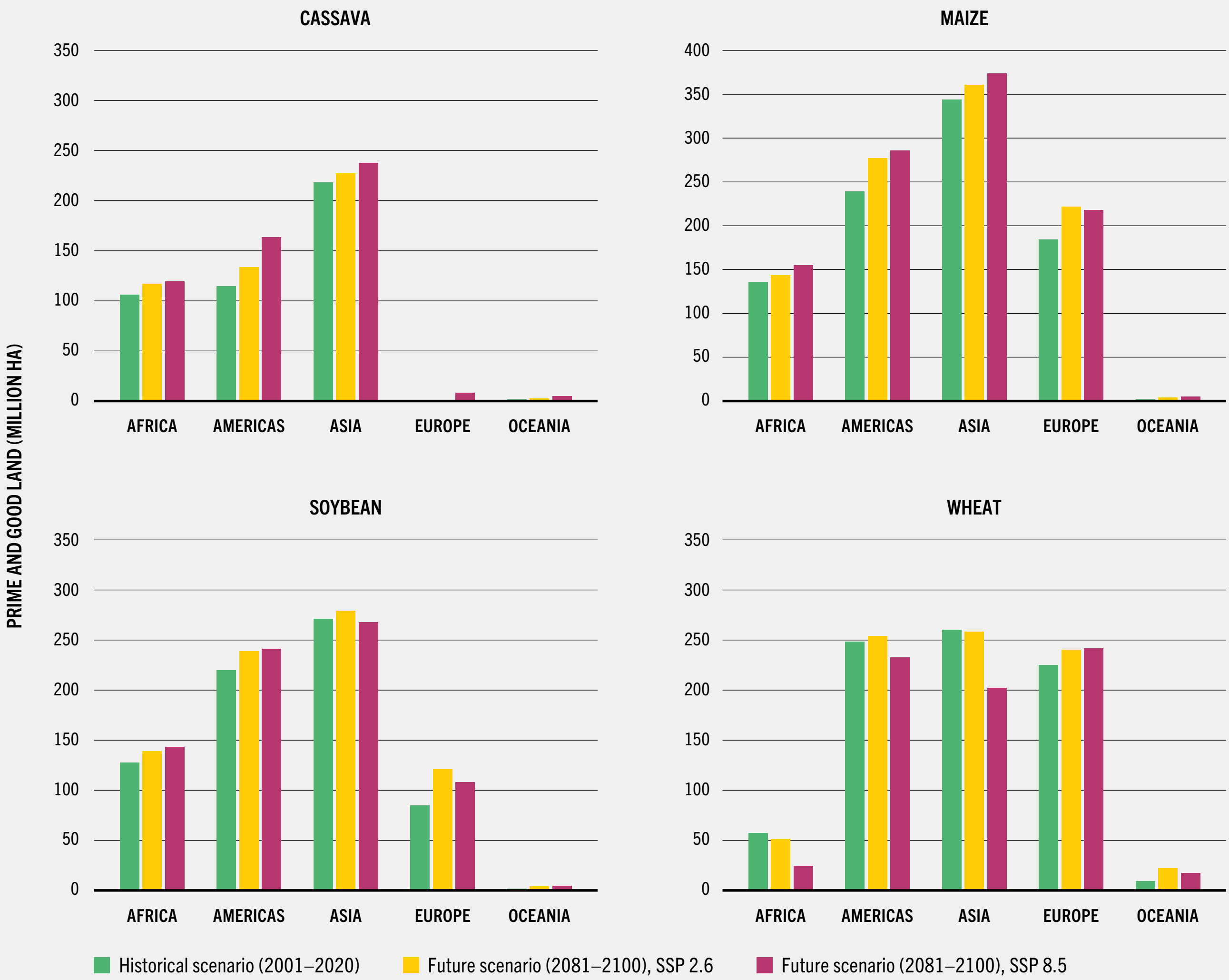
SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

emission levels represented by Representative Concentration Pathways (RCPs) (see the **Annex** for details). More specifically, the analysis on climate change impact used results from the GAEZ v5 historical scenario (2001–2020) and from an ensemble mean scenario for the period 2081–2100 under two climate scenarios: SSP 2.6 – assuming low emissions and significant climate mitigation efforts; and SSP 8.5 – representing a worst-case scenario with minimal mitigation. Trends were assessed separately for four selected crops – maize, wheat, cassava and soybean – under rainfed conditions.

Climate change is projected to alter the distribution of suitable areas for the crops analysed (see Table 9 and Figure 23). Under the SSP 2.6 scenario, global results foresee a net increase in prime and good land suitable for all crops. Results across regions and crops show consistent patterns, with Europe and Oceania experiencing the largest increases, the Americas showing intermediate gains, and Africa and Asia projected to have the least increase. In the specific case of wheat, Africa and Asia are projected to experience some reduction in suitable land even under this moderate scenario, a pattern that becomes more pronounced under the SSP 8.5 worst-case projections.

Under the SSP 8.5 scenario and with an assumption of advanced management conditions in place, projections indicate a net increase in suitable areas for cassava, maize and soybean, but an overall reduction for wheat. This does

FIGURE 23 HISTORICAL AND PROJECTED EXTENT OF SUITABLE (PRIME AND GOOD) LAND UNDER RAINFED CONDITIONS BY REGION FOR FOUR MAIN CROPS UNDER DIFFERENT CLIMATE SCENARIOS



NOTES: SSP – Shared Socioeconomic Pathway. The analysis compares the extent of suitable land between the historical scenario (2001–2020) and future projections (2081–2100) under the SSP 2.6 (low emissions) and SSP 8.5 (high emissions) climate scenarios. Totals include suitable land with prime and good suitability for each crop under rainfed conditions.

SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

https://doi.org/10.4060/cd7488en-fig23

not necessarily imply higher production of the three aforementioned crops, as the scenarios do not take into account extreme events and socioeconomic factors; the analysis shows the maximum potential, not actual outcomes, under the assumption of ideal biophysical and socioeconomic conditions. For wheat, the largest negative impact is projected in Africa, with a 57 percent reduction from its historical 57 Mha of prime and good land. Asia is also projected to experience a substantial reduction in areas suitable for wheat, with a 22 percent decrease from the 260 Mha of prime and good land in the historical scenario. It should be noted, however, that these findings focus on changes in suitable areas for the selected crops, while increased suitable land does not always correlate with increased productivity (Jägermeyr *et al*., 2021), especially if climate stressors limit yields even in newly suitable areas. For paddy rice (not shown in the table), the analysis reveals important increases in water demand: +25 percent and +45 percent in the Americas and Europe, respectively, and limited reductions in the other regions.

Additional insights may be gained by looking at the spatial distribution of the projected change under future climate scenarios. Figure 24 shows projected climate change impacts on land suitability under SSP 8.5, representing the highest increase in emissions and climate warming, while Figure 25 provides results for the SSP 2.6 scenario.

Under the SSP 8.5 scenario, cassava is projected to gain additional land suitable for cultivation, including in areas where this crop is not currently grown. Notably, significant increases in suitable land are anticipated in Australia, China and the United States of America. Conversely, large cassava-producing countries, such as Zambia and Zimbabwe, are projected to face a decline in the area suitable for this crop. The GAEZ assessment of crop suitability under future climate scenarios assumes optimized management levels and focuses exclusively on rainfed conditions. Since the GAEZ analysis also integrates terrain and soil constraints, direct comparison with results from a recent study on future crop suitability (Mombo *et al*., 2025) is challenging. Nevertheless, both assessments agree that crop suitability under the most adverse climate conditions is likely to exhibit substantial geographical variability, largely influenced by other factors such as water availability, agricultural inputs and mechanization. The results here are at global level, so consideration should be given to national and local biophysical and socioeconomic conditions when applying the findings.

The area suitable for maize cultivation is projected to increase significantly in Northern America, Northern Europe and the Russian Federation, as well as across Sahelian countries. In contrast, decreases in suitable land are projected in China and Southern Africa, while India and most South-eastern Asian countries are expected to see negligible changes in maize suitability.

Overall, the impact of climate change on soybean appears less pronounced. Climate change is anticipated to positively affect soybean cultivation by expanding suitable areas in Canada, Northern Europe, the Russian Federation and the United States of America, However, reductions in suitable land are also projected in Western Europe. In the Southern Hemisphere, changes are projected to be less dramatic. Brazil, the world's leading soybean producer, is expected to see some increase in suitable areas, including regions currently under different land uses. Several Southern African countries are projected to face a decline in suitable areas for soybean cultivation under the SSP 8.5 high-emissions scenario.

As indicated earlier, climate change is expected to adversely affect suitability for cultivating wheat in several regions. Under the SSP 8.5 scenario, significant reductions in suitable land are projected in Brazil, Eastern and Southern African countries, and in large parts of China and India. Conversely, increases in wheat suitability are anticipated in Canada and the western regions of the United States of America, as well as in parts of Western Asia. These trends align with findings that global warming will polarize wheat suitability, with colder regions at mid-to-high latitudes benefiting from improved conditions, while low-latitude regions are expected to face substantial declines due to rising temperatures (Guo, Zhang and Yue, 2024).

Climate change is anticipated to significantly alter the global agricultural landscape, creating opportunities for some and exacerbating constraints for others. By 2100, the northern high latitudes are expected to gain substantial agricultural land, while tropical regions will experience losses. This shift underscores the need for countries to adapt to changing conditions by implementing strategic and effective responses. Adaptation strategies such as crop diversification and shifting to more resilient options are especially important. Policy and technical support for farmers transitioning to new crops or practices are crucial. At national level, some of these changes will alter the balance between supply and demand for staple products, with consequences for food trade.

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FIGURE 24 IMPACT OF CLIMATE CHANGE ON THE EXTENT OF PRIME AND GOOD LAND FOR FOUR CROPS UNDER RAINFED CONDITIONS, SSP 8.5

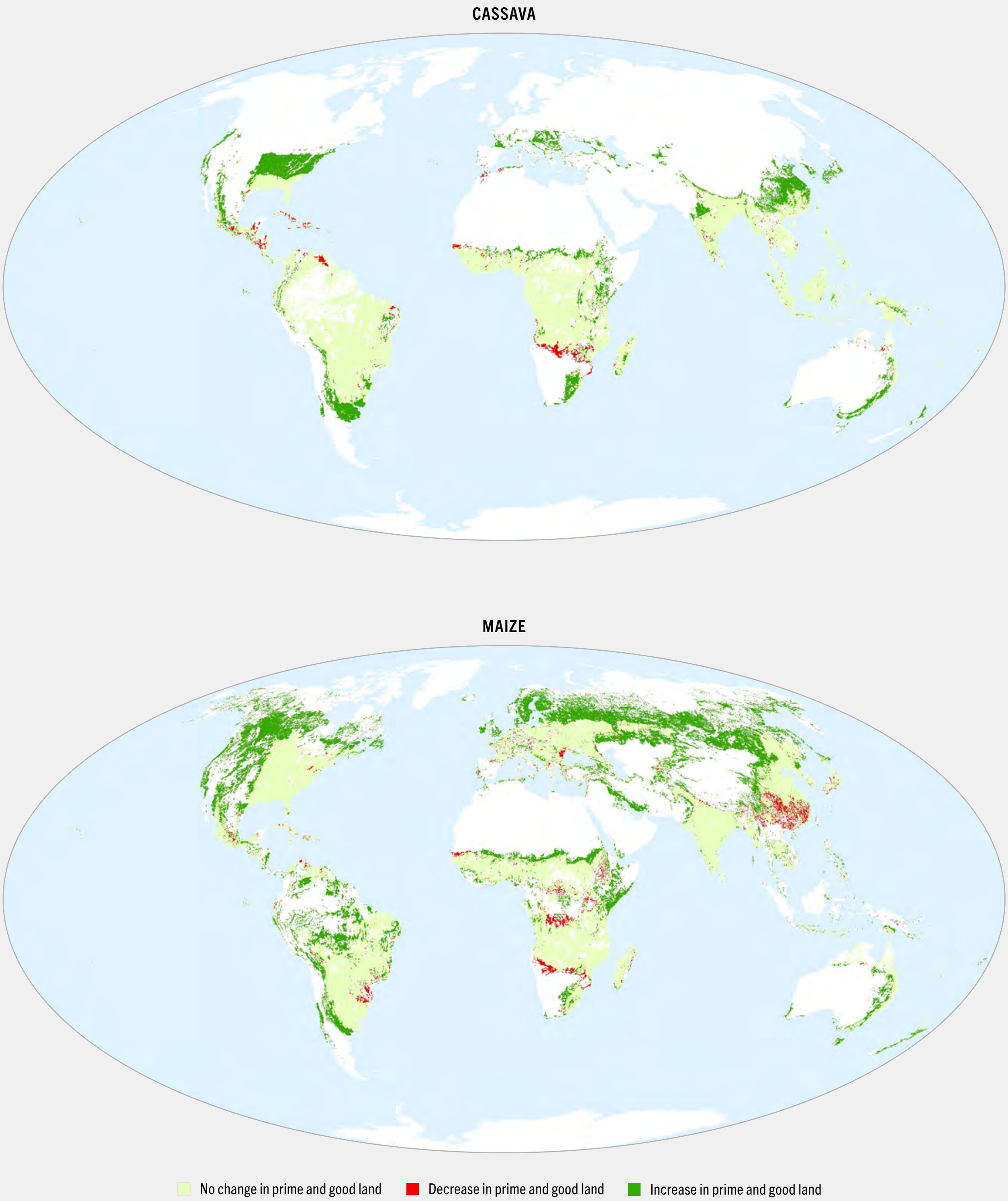
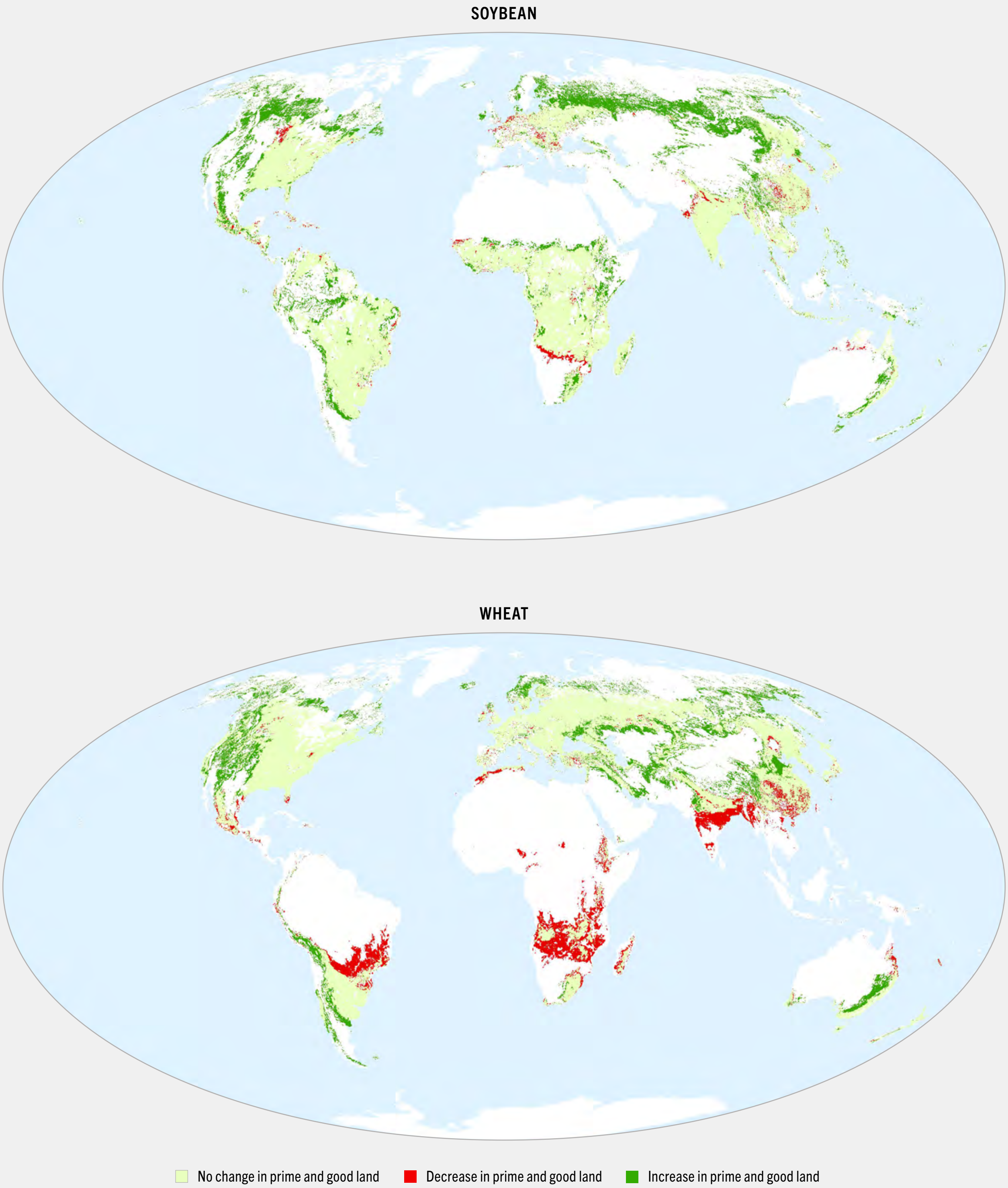


FIGURE 24 (Continued)



Refer to the disclaimer on the copyright page for the names and boundaries used in these maps.

NOTE: The analysis compares the distribution of suitable land between the historical scenario (2001–2020) and future projections (2081–2100) under the SSP 8.5 high-emissions climate scenario.

SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

FIGURE 25 IMPACT OF CLIMATE CHANGE ON THE EXTENT OF PRIME AND GOOD LAND FOR FOUR CROPS UNDER RAINFED CONDITIONS, SSP 2.6

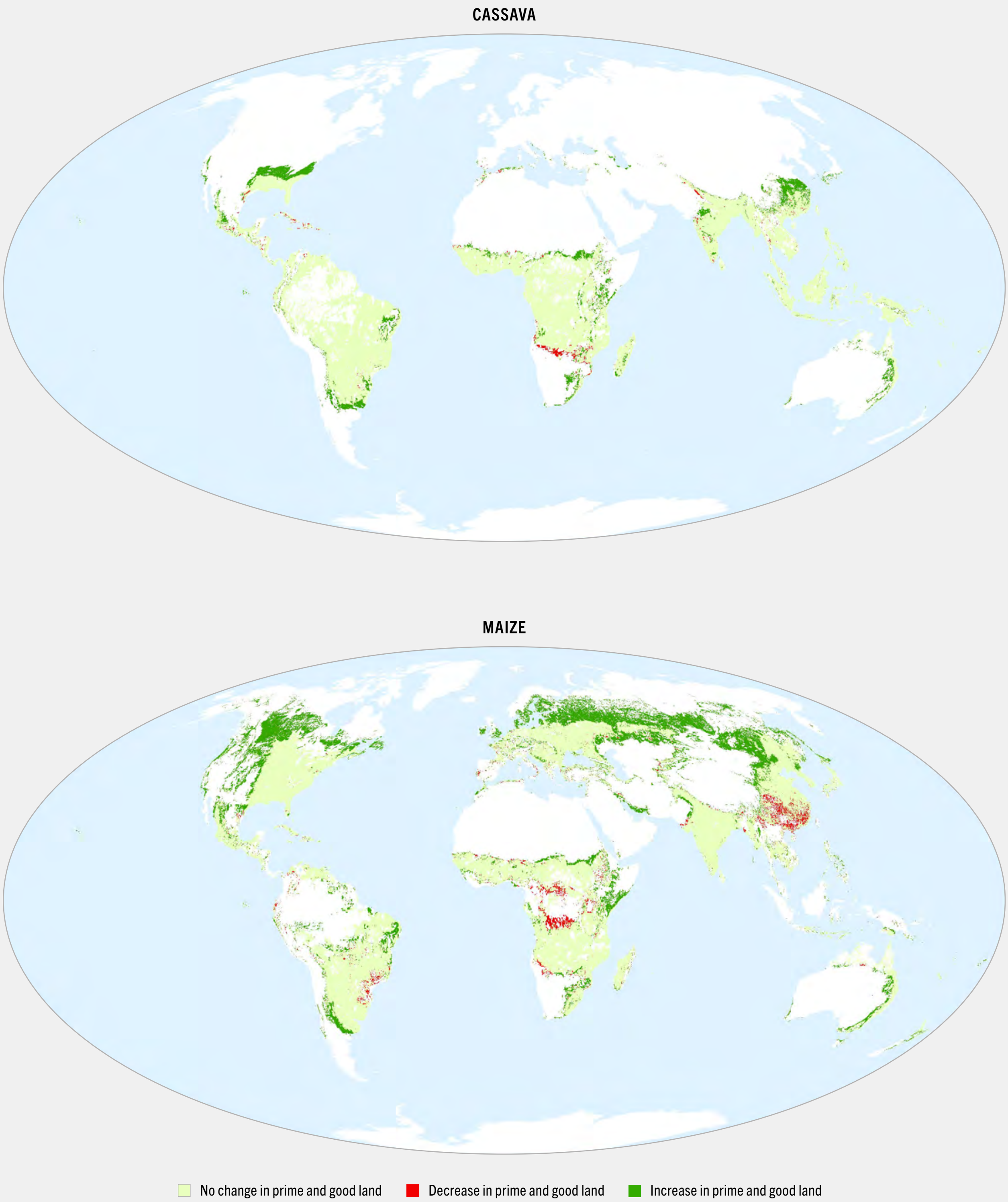
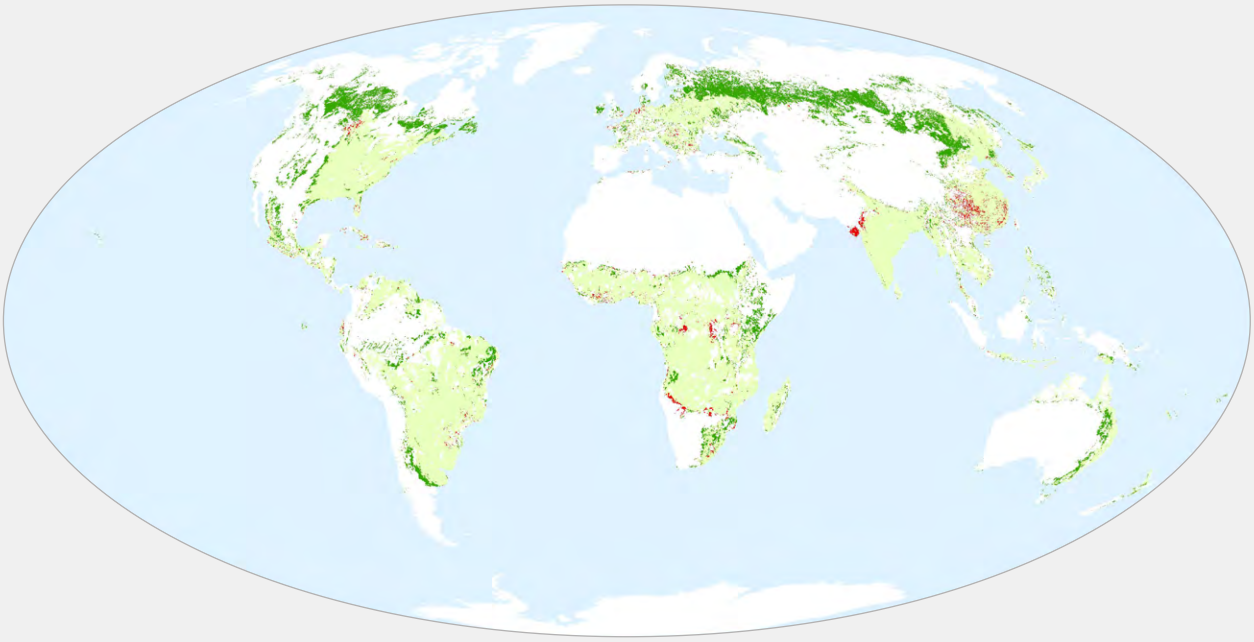
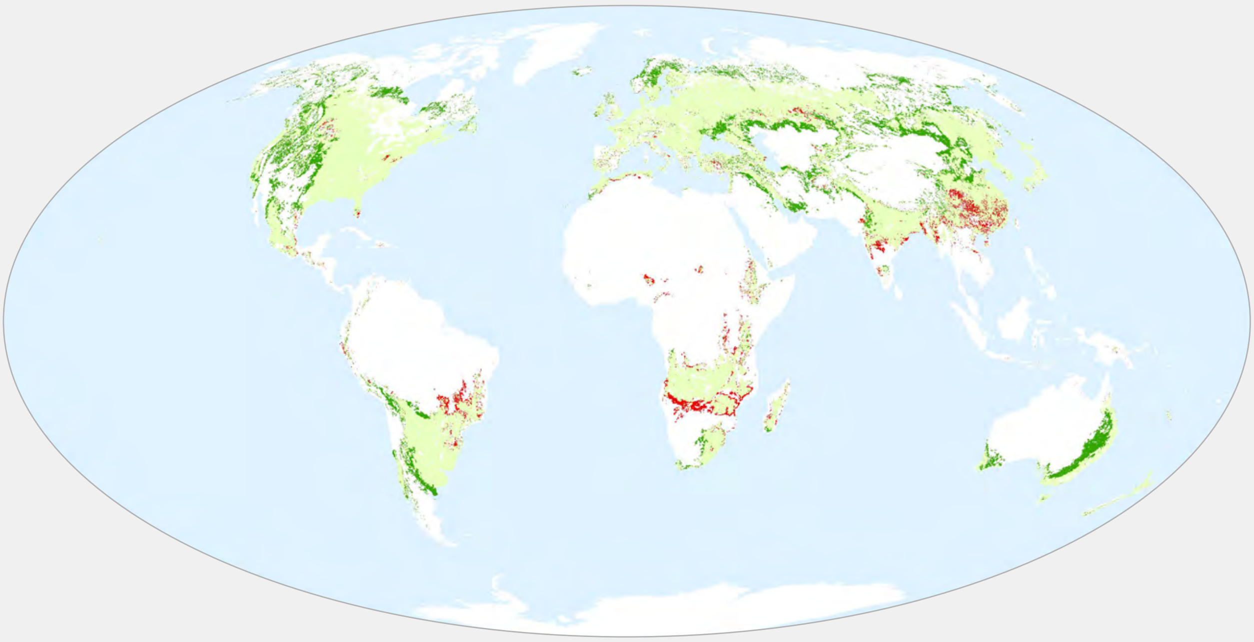


FIGURE 25 (Continued)

SOYBEAN



WHEAT



No change in prime and good land | Decrease in prime and good land | Increase in prime and good land

Refer to the disclaimer on the copyright page for the names and boundaries used in these maps.

NOTE: The analysis compares the distribution of suitable land between the historical scenario (2001–2020) and future projections (2081–2100) under the SSP 2.6 low-emissions climate scenario.

SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation.* [Cited 13 February 2025]. https://www.fao.org/gaez/en

TABLE 10 NET IRRIGATION DEMAND IN THE HISTORICAL PERIOD (2001–2020) AND PERCENTAGE VARIATIONS IN THE FUTURE (2081–2100) UNDER SSP 2.6 (LOW EMISSIONS) AND SSP 8.5 (HIGH EMISSIONS) CLIMATE SCENARIOS

Region	Maize			Wheat		
	Historical (2001–2020)	Future (2081–2100)		Historical (2001–2020)	Future (2081–2100)	
	mm/crop growth cycle	SSP 2.6 Variation (%)	SSP 8.5 Variation (%)	mm/crop growth cycle	SSP 2.6 Variation (%)	SSP 8.5 Variation (%)
Africa	614	1	3	211	–2	10
Americas	275	–4	18	95	–15	–24
Asia	405	3	1	228	–11	–24
Europe	172	9	87	310	–15	–22
Oceania	521	–11	0	211	–21	–13

NOTES: SSP – Shared Socioeconomic Pathway. Values are computed for prime and good land in irrigated cropland.

SOURCE: Authors' own elaboration based on FAO & IIASA. 2025. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

» While the impact of climate change on crops is relatively easy to predict, the possible impact on other agricultural production systems such as livestock is much more complex and less well known (Thornton *et al.*, 2009). While heat stress is often seen as the prime expected impact on livestock in all countries except cold countries, the impact on animal feed may become increasingly important as rainfall becomes more erratic and the frequency and intensity of droughts increase, affecting both croplands and rangelands.

Agricultural water demand under climate change

GAEZ measures crop-specific water deficits considering the balance between evapotranspiration and precipitation, a reference soil water retention capacity and the actual soil and terrain conditions for each grid cell (Fischer *et al.*, 2021). Table 10 compares water demand for maize and wheat between the historical period 2001–2020 and two future climate change scenarios: low emissions (SSP 2.6) and high emissions (SSP 8.5). In GAEZ, water demand corresponds to the amount of irrigation water that is needed to reach the plant in order to fully meet crop water requirements. In general, together with changes in temperature regime and precipitation during the crop cycle, other factors such as the shift of the crop calendar or the selection of different crop varieties may contribute to changes in water requirements.

The results show significant differences in crop water requirements across the scenarios and across the regions for maize and, to a lesser extent, for wheat (see Table 10). Wheat is projected to undergo notable changes in water demand under both future scenarios. Africa is the only region where water requirements for wheat are expected to increase under high-emissions scenarios, whereas all other regions are projected to experience reductions in water demand. ■

SENEGAL
A woman collects water from a rainwater harvesting cistern in the village of Douly.
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CHAPTER 4
SUSTAINABLE LAND AND WATER RESOURCES MANAGEMENT: TECHNICAL SOLUTIONS

KEY MESSAGES

➔ Multiple technical solutions exist to achieve sustainable land, soil and water management. They depend on the socioecological context and production system. Their adoption by land and water users requires that the solutions be accompanied by the appropriate enabling environment.

➔ The productivity of rainfed agriculture can be improved through a more systematic adoption of conservation agriculture and the use of drought-tolerant crop varieties and drought-resilient practices such as soil moisture conservation, crop diversification and organic composting. These practices have the potential to make a significant contribution to the food security of millions of smallholder producers and to enhance soil health and on-farm biodiversity.

➔ Enhancing the productivity of water in irrigation can be achieved through a combination of water management and agronomic practices. Modernization of irrigation is the key to reducing yield gaps and increasing water productivity. For the long-term success of modernized irrigation systems, a benchmarking approach that encompasses technical, institutional, socioeconomic and environmental factors is needed.

➔ Approaches that contribute to better land and water management for pasture and feed production include improvement of water management and grazing practices, selection of drought-tolerant and water-efficient species (e.g. perennial forage grass), integration of alternative forage and legumes in pastures, and precision livestock farming technologies.

➔ The importance of urban and peri-urban agriculture (UPA) in the world's food production systems is growing. Hydroponics and vertical and rooftop farming are proven techniques used in cities around the world to increase the efficiency of UPA and reduce competition for land, water, energy and labour.

➔ Forests sustain the livelihoods of millions and contribute to global objectives such as climate change mitigation and adaptation, as well as biodiversity conservation. Restoring degraded lands, promoting agroforestry, and building green value chains for forest products, including non-wood forest products, are critical for maintaining and tapping the potential of forests and trees for sustainable agrifood systems.

➔ Inland fisheries face significant threats from competition for water and land resources. While offering major potential for increased fish production, inland fisheries require an integrated approach to water management. Techniques such as cutting channels through levees to connect rivers with adjacent floodplains allow fish to migrate and spawn during flood seasons. Inland aquaculture – a rapidly growing practice – also offers opportunities for integrated food production: rice–fish farming systems are a prime example and contribute to both farm incomes and nutrition, while simultaneously using water more efficiently.

➔ Integrating sectoral solutions offers a unified model for sustainable land, water, forest and aquatic resource management that addresses multiple aspects of food security, climate resilience and environmental sustainability. Agroforestry, rotational grazing and forage improvement, and rice–fish farming are just a few examples of such integrated approaches. Together, these technologies and practices create a framework where sustainable resource use is tailored to specific landscapes and enhances resilience to climate change.

To reverse the trends associated with the unsustainable management of land and water resources and ensure global food security, land and water users around the world need to adopt technologies, practices and approaches that enhance ecosystem health, resilience and productivity, while ensuring inclusiveness and improving the livelihoods of the most vulnerable populations.

Appropriate governance, legal and regulatory frameworks, finance, research, extension services and market development are all elements of the enabling environment needed to support the adoption of these practices. Institutional support and an enabling environment are further discussed in **Chapter 5**.

Recognizing that there is no one-size-fits-all solution and given the wide array of often context-specific technical solutions, practices and innovations across different sectors, this chapter is not exhaustive and presents a few examples of technical options and innovations for sustainable plant production and protection; land and water management in irrigated and rainfed systems; urban and peri-urban agriculture (UPA); rangeland, pastureland and forest and agricultural land restoration; and integration of inland fisheries and aquaculture within land-based agricultural systems. In addition, the chapter shows the interconnectedness between sectoral approaches and the need to adopt integrated solutions. Many of the approaches discussed here are aligned with and contribute to the UNCCD Land Degradation Neutrality objectives (Hartmann *et al*. 2024).

Technological solutions depend on socioecological context and production systems, of which there are a wide variety around the world. Practices need to be matched with land suitability to ensure that they are both sustainable and profitable and that they contribute to inclusive rural transformation.

Crop-based food production systems (rainfed and irrigated) are the most widespread, but these are not the only options. Agricultural lands, including pasture systems that support livestock production, also have global relevance. Forests account for up to 25 percent of rural household income in tropical and subtropical countries (FAO, 2022a). Non-wood forest products (NWFPs) play an important role in providing food, income and nutritional variety for millions of people worldwide. Inland fisheries produce about 12 percent of global fish supply, with 90 percent of production coming from small-scale fisheries (FAO, 2024a). The rapid growth of inland aquaculture, which now accounts for 63 percent of total aquaculture production, demonstrates its potential to support food systems, with freshwater fish supplying organic protein and nutrients. ■

TECHNICAL OPTIONS FOR RAINFED AGRICULTURE

Rainfed agriculture accounts for 52 percent of global crop production and is practised in areas where precipitation is usually sufficient to secure good harvests. This type of agriculture is common in a wide range of farming situations, from large- to small-scale systems. It supports millions of smallholder farmers in developing countries, with diverse cropping patterns that ensure income and food security and maintain biodiversity. Key staple crops grown under rainfed conditions include cereals and pulses.

When practised correctly, rainfed agriculture contributes to enhanced production, nutrition and environmental sustainability. Diversified cropping patterns support nutritious diets while increasing the resilience of farming practices. Practices such as crop rotation and cover cropping improve soil health and biodiversity. Technical innovations such as integrated plant nutrient management, integrated pest management, the adoption of drought-resistant crops, and water harvesting and soil management techniques are essential to boost the productivity of rainfed agriculture in a sustainable way.

The following are examples of technologies that contribute to addressing current challenges in rainfed agriculture.

Conservation agriculture

Conservation agriculture (CA) combines practices that help to preserve soil moisture,

BOX 5 FAO'S AGRICULTURAL STRESS INDEX SYSTEM

FAO has developed the Agricultural Stress Index System (ASIS) for the early identification of agricultural areas prone to being affected by dry spells or, in extreme cases, drought. The system has been in operation since July 2014 and is updated three times per month, as soon as new satellite data become available. The ASIS annual and multi-annual data archive (dating back to 1984) also contributes to various climate and socioeconomic studies.

The system focuses on detecting areas where crops are under stress due to water scarcity, providing timely information to decision-makers and farmers so that they can mitigate the impacts of drought. In addition, with the integration of artificial intelligence-driven climate models and satellite data, decision-makers can now better predict drought events and make informed decisions about water management and planting schedules (Cancela *et al*., 2019).

prevent runoff and erosion, and maintain soil structure; they include minimum tillage, cover cropping and crop rotation. Since 2008–2009, the CA cropland area has been expanding globally at a rate of more than 10 Mha per year. In 2015–2016, global CA cropland area was 180.4 Mha, corresponding to 12.5 percent of the total cropland area. In 2018–2019, global cropland area was 205.4 Mha, corresponding to 14.7 percent of total cropland area (Kassam, Friedrich and Derpsch, 2022). Conservation agriculture increases water infiltration and soil moisture conservation, and it reduces soil erosion by 50 percent (Pittelkow *et al*., 2015). In Southern Africa, where these practices have been widely adopted, crop yields increased by 15 to 25 percent and soil degradation was significantly reduced (Pittelkow *et al*., 2015).

Drought-tolerant varieties and drought-resilient practices

The development of drought-tolerant crop varieties is vital for maintaining productivity in rainfed systems facing increasingly erratic rainfall patterns due to climate change. FAO's Global Partnership Initiative for Plant Breeding Capacity Building has contributed to improve food security in arid regions worldwide by promoting drought-resistant crop varieties (FAO, 2025a). In Africa, for example, the introduction of drought-tolerant maize has led to significantly higher yields and reduced crop failure rates (Abate *et al*., 2017).

Rainwater harvesting and soil moisture conservation help to mitigate the impacts of drought and ensure more stable food production in rainfed agriculture. To cite just one case, Ethiopia has experienced notable success in using rainwater harvesting systems to boost crop yields and enhance resilience during dry seasons (Mekonnen *et al*., 2022).

In addition to these on-the-ground practices, early warning systems and climate forecasting tools play a crucial role in supporting both rainfed and irrigated farming. The FAO Agricultural Stress Index System (ASIS) is an example of an early warning tool designed to monitor agricultural droughts and assess crop conditions using satellite-based data (see Box 5).

Crop diversification, composting and raised beds

Crop diversification and organic matter management are two important components of sustainable farming strategies. Crop diversification can contribute to better use of water and nutrients, improved plant health and enhanced overall farm productivity through a combination of practices such as well-planned crop rotations and biological pest control. Soil organic matter management, through green manuring, mulching and composting, helps to enhance the accumulation of organic matter in the soil and nutrient cycling (Altieri and Nicholls, 2018). Box 6 presents an example of the application of such practices in Cuba.

BOX 6 CROP DIVERSIFICATION, COMPOSTING AND RAISED BEDS IN CUBA

In Cuba, crop diversity, water efficiency, organic matter recycling and crop–animal synergies in raised beds over a 30-year period have enabled the supply of more than 50 percent of the fresh foods consumed in the country, while simultaneously creating 300 000 jobs and contributing over 1 million tonnes of food annually (RUAF, 2017).

Raised beds provide a medium for intensive crop production in soil elevated above the surrounding ground level, reducing exposure to contaminated soil from previous land uses (Altieri and Nicholls, 2018). By easing the management of crops, due to their elevation from the soil, raised beds also contribute to improving yields per unit of labour input (FAO, 2020a). The farmer-to-farmer movement launched by the Cuban National Association of Small Farmers in an effort to co-create and share knowledge has been a driving force for the adoption of improved practices that embrace agroecology (RUAF, 2017).

Composting is particularly relevant in urban and peri-urban settings where organic waste is abundant. The Madrid Agrocomposta municipal initiative has converted 23 tonnes of residents' food waste into compost and fixed 2 400 kg of CO_2eq in the soil since 2016 (Agrocomposta, 2021). Agroecology also presents a significant opportunity for recycling urban food waste. Ecuador's AGRUPAR programme has successfully supported local food production in underutilized spaces in Quito, benefiting 1 300 productive units and enhancing social inclusion via farmers' markets through responsible governance. Similar human and social values have guided interventions in Taiwan Province of China, where Indigenous Peoples' research has made it easier to reclaim land rights. In Gorakhpur, India, low-external input practices such as management of effective microorganisms have significantly increased farmers' incomes and resilience, illustrating the economic benefits of agroecological approaches (RUAF, 2017). Meanwhile, the ØsterGRO Community-Supported Agriculture initiative in Copenhagen embodies circular and solidarity economy as well as cultural and food tradition elements, fostering direct producer–consumer relationships and local foods while minimizing food and packaging waste by avoiding supermarket intermediaries (Shaw, 2017). ■

TECHNICAL OPTIONS FOR IRRIGATED AGRICULTURE

Latest estimates based on FAOSTAT data indicate that around 22.5 percent of the world's cultivated land is currently irrigated, accounting for approximately 48 percent of global crop production (see **Chapter 2**). As irrigation plays an increasing role in agricultural production, better use of water in agriculture becomes increasingly important.

Improving irrigation water productivity

There is considerable scope for improving water productivity in agricultural systems around the world. Many farmers in developing countries could increase water productivity by adopting proven agronomic and water management practices; this is because raising land productivity generally leads to increases in water productivity. Promising pathways for raising water productivity are available along the continuum from fully rainfed to fully irrigated farming systems. These include supplemental irrigation (irrigation supplements rainfall); soil fertility maintenance; deficit irrigation (the crop is irrigated with water below the full requirement for optimal plant growth, to increase crop water productivity); small-scale practices for water storage, delivery and application; pressurized irrigation technologies (e.g. sprinkler and drip irrigation);

and soil and water conservation through zero or minimum tillage. The choice of the most appropriate technologies depends on a range of factors, including climatic conditions, sources and cost of energy, labour availability, depth of groundwater sources, and infrastructure costs.

Reducing evaporation from the soil while increasing productive transpiration by plants can also enhance water productivity. Evaporation can account for a very high share of evapotranspiration in rainfed systems with low plant densities. Perhaps surprisingly, drip and sprinkler irrigation systems do not necessarily result in less evaporation than good surface irrigation systems (Burt, Howes and Mutziger, 2001). Practices to shade the ground (e.g. mulching, ploughing or plant breeding for fast leaf expansion) reduce evaporation and increase productive transpiration.

Increasing economic water productivity (more value per unit of water) can be done by switching to higher-value agricultural products or by reducing production costs. Integrated approaches such as agriculture–aquaculture systems, better integration of livestock in irrigated and rainfed systems, and use of irrigation water for household and small industries, can all make a significant contribution to increasing the value per drop. For example, better veterinary services can improve water productivity because healthier animals provide more benefits per unit of water.

Modernization of irrigation schemes

Irrigation infrastructures developed during the twentieth century increasingly require technical and managerial upgrades to ensure that they respond to the need for productive and sustainable agriculture. Increasing competition for resources requires the adoption of multicriteria analysis to prioritize irrigation schemes for modernization,[h] integrating digital and modern techniques, strengthening water governance and policy frameworks, integrating environmental considerations and ecosystem-based solutions, and promoting data-driven irrigation practices. Both farmers and policymakers are frequently keen to introduce modernization. However, irrigation modernization is financially resource-intensive and requires a careful prioritization process.

In Spain, over a period of two decades, around 20 percent of the country's irrigation units were modernized. Modernization efforts were found to improve water management capacities, enhance crop yields and reduce energy costs, but the abandonment of marginal and structurally deficient irrigated areas remains a concern for the local population. A critical challenge was that public co-funding and policy-driven efforts were insufficient to address the needs of all irrigated areas, and a significant proportion of irrigation units remain reliant on obsolete irrigation infrastructure (Playán *et al.*, 2024).

A systematic approach to prioritizing irrigation systems for modernization should be based on multiple criteria. The Prioritization of Irrigation Schemes for Modernization/Rehabilitation (PRISM) tool developed by FAO (Pek, 2022) evaluates various critical factors to help decision-makers allocate resources effectively. These include water availability and water-use efficiency, system performance, potential productivity gains, environmental sustainability and socioeconomic benefits. By considering these criteria, PRISM helps to identify irrigation systems where modernization investments can yield the most substantial benefits. One of the core strengths of this tool is its ability to guide data-driven decision-making, ensuring that irrigation modernization is based on robust, evidence-based assessments (see Box 7). The tool integrates both technical and socioeconomic factors, providing a balanced evaluation of each system. Its flexibility enables it to be adapted to specific local and national conditions, enhancing its usefulness across various regions. By promoting irrigation system upgrades in locations that have the greatest potential for efficiency and productivity improvements, PRISM aligns modernization efforts with global goals for sustainable food production.

Remote sensing and drone technology can be leveraged to guide irrigation scheme modernization

h Irrigation modernization is "a process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes combined with institutional reforms, with the objective to improve resource utilization (labour, water, economic, environmental) and water delivery service to farms" (FAO, 1998).

BOX 7 PRIORITIZATION OF IRRIGATION SCHEMES FOR MODERNIZATION/REHABILITATION IN TAJIKISTAN

In Tajikistan, the Prioritization of Irrigation Schemes for Modernization/Rehabilitation (PRISM) tool has been applied to guide the prioritization of irrigation systems requiring modernization in the Zarafshon Basin (Pek, 2022). The country's reliance on irrigation for agricultural production, coupled with an ageing infrastructure and water scarcity issues, made it a prime candidate for the application of PRISM. The tool has helped to identify high-priority systems where investments could yield the most substantial benefits in terms of productivity gains and water resources management.

Its use in Tajikistan demonstrates the tool's effectiveness in guiding national-level irrigation policy and investment strategies. By applying PRISM, decision-makers were able to target systems mostly in need of modernization, optimizing resource allocation and achieving more sustainable outcomes.

BOX 8 ENHANCING WATER-USE EFFICIENCY THROUGH REMOTE SENSING DRONE TECHNOLOGY IN LEBANON

In the Akkar region of Lebanon, the El-Bared Canal system – a primary irrigation source for approximately 42 000 ha of land – suffers from severe infrastructure decay and pollution due to human interference and limited maintenance. The Rehabilitation of El-Bared Canal Irrigation System project, funded by the Government of Norway, was implemented to revitalize agriculture in the region. A significant component of the project was irrigation infrastructure modernization, leveraging remote sensing technology, particularly through drone-based damage assessment to enhance water-use efficiency.

Using quadcopters (drones), high-resolution orthophotos of the canal bed were taken to assess the rehabilitation needs of the Akkar irrigation canal. An image-processing algorithm was developed to analyse the requirements by differentiating between damaged and undamaged surfaces. A topographic survey was conducted to validate the process by overlaying drone data with actual structural measurements. The approach produced precise and scalable data, revealing a clear pattern of increased canal damage in areas of high population density and increased human interaction with the irrigation infrastructure for accessing water.

Lessons learned:

- **Data accuracy** – High-resolution imagery and optimized altitudes significantly enhanced image quality and the accuracy of analysis, and optimized cost-effectiveness.
- **Process automation** – The success of automated image segmentation shows potential for wider application in the assessment of large-scale irrigation systems.
- **Adaptability** – Remote assessment proved essential for continuous monitoring of inaccessible sections of the irrigation system facing infrastructure decay and pollution challenges.

Scaling up across large irrigation networks could help to enhance water management in irrigation schemes, increase agricultural productivity and improve resource-use efficiency.

and enhance water-use efficiency. Box 8 shows how such technology was used in Lebanon.

Developing a holistic benchmarking approach for irrigation modernization

Irrigation modernization demands a comprehensive benchmarking approach that goes beyond mere technical upgrades. While structural modifications – such as transitioning from open canals to pressurized piping, and automating water release systems – represent significant advances, the success of these innovations hinges on various interrelated factors. To truly realize the potential of irrigation modernization, the benchmarking approach must encompass four main types of factors: technical, institutional, socioeconomic and environmental (see Box 9). A comprehensive analysis of these factors facilitates the identification of effective strategies that address the complexities of irrigated agriculture, ultimately fostering resilience and long-term success in modernized irrigation systems. ■

BOX 9 FOUR FACTORS FOR SUCCESSFUL IRRIGATION MODERNIZATION BENCHMARKING

Technical. The underperformance of aged irrigation schemes around the world can be attributed to a range of technical factors that significantly hinder their effectiveness. Many of the technologies introduced during the initial design phase are no longer appropriate for local conditions, leading to inefficient water delivery and widespread water wastage. Poor infrastructure maintenance often results in substantial water losses, compounding the challenges faced by farmers.
To address the technical shortcomings, modernization plans should include appropriate irrigation technologies, alongside a comprehensive rehabilitation of existing infrastructure. Integration of technical capacity-building programmes for farmers about water-efficient technologies can also enhance irrigation performance, ensuring that they are better equipped to manage their water resources effectively.

Institutional. In the past, irrigation schemes were operated under top-down management structures, limiting users' participation. Centralized management often results in information gaps between decision-makers and the realities on the ground, leading to ineffective water allocation and management. The governance of local institutions responsible for managing water resources, such as water users' associations (WUAs), is often weak, lacking the authority and resources necessary to operate effectively. This inadequate institutional capacity can lead to inequitable service delivery and may result in conflicts over water use. Fragmented policy frameworks further complicate these issues, as inconsistent regulations hinder the coordination necessary for effective water management. Empowering local communities and strengthening WUAs or farmers' associations through capacity-building initiatives and appropriate local institutional frameworks should be central to all modernization efforts and included in any benchmarking exercise. Creating integrated institutional frameworks that align water management with food production goals can also foster better coordination among stakeholders, ultimately improving the overall management of irrigation systems.

Socioeconomic. Contributing to the challenges facing irrigation are a range of socioeconomic factors such as poor market access. Weak market linkages often prevent farmers from selling their produce competitively, diminishing their motivation to invest in improved irrigation systems. Improving market infrastructure to facilitate better access to markets will motivate farmers to adopt more efficient irrigation practices. In many cases, lack of landownership and insecurity of tenure deter farmers from investing in irrigation infrastructure or adopting new practices due to fears of losing access to land. Modernization should involve land tenure reforms to provide farmers with secure land rights, encouraging long-term investments in irrigation. Furthermore, smallholder farmers typically encounter significant barriers when seeking financial support, making it difficult for them to access the finance they need to upgrade their irrigation systems. Establishing financial support mechanisms, such as subsidized loans or grants, can help smallholders to access the resources they need to enhance their irrigation systems, ultimately leading to more sustainable agricultural outcomes.

Environmental. In modernizing irrigation systems, it is essential to prioritize environmental safeguards in order to enhance sustainability. Key considerations include conserving biodiversity by protecting local ecosystems and maintaining habitat corridors, as well as ensuring better water quality through monitoring and integration of ecosystem-based solutions (vegetative buffers) to filter contaminants. Additionally, integrating climate adaptation strategies, engaging local communities in decision-making and adopting integrated water resources management approaches can promote resilience to climate change. Finally, using renewable energy sources for irrigation operations can significantly reduce greenhouse gas emissions, contributing to a more sustainable agricultural future.

TECHNICAL OPTIONS FOR CROP PRODUCTION IN URBAN AND PERI-URBAN CONTEXTS

Estimates indicate that urban agriculture contributes 5 to 10 percent of global production of pulses, roots, tubers and vegetables (Clinton *et al*., 2018). Due to rapid urbanization worldwide, the importance of UPA as a component of the world's food production systems is growing (FAO, Rikolto and RUAF, 2022). Urban and peri-urban agriculture is mainly based on horticulture, but also includes livestock keeping (e.g. small ruminants, poultry and swine), aquaculture (e.g. fishponds) and agroforestry. It competes for resources (land, water, energy and labour) with other types of activities in and around cities. This section describes some of the technologies and approaches used to increase efficiency in UPA.

Hydroponics

Hydroponics is an agricultural technique that enables plant growth without soil (FAO, 2023). All the water and nutrients necessary to sustain plant growth are provided through a liquid solution, while various inert media and structures offer essential physical support for root and stem development.

Compared with conventional soil-based farming, hydroponics is more intensive – in terms of capital, technology and inputs. At the same time, it offers significant advantages to producers, for example, the elimination of soil-borne diseases, efficient use of water, nutrients and labour, increased plant density, and quicker crop succession (Jones, 2014).

Hydroponics aims to optimize input-use efficiency and achieve predictable harvests by protecting crops from excessive rain, heat and low temperatures. This is often done by integrating hydroponics with protected cultivation systems such as greenhouses (Resh, 2022). The combination of protected cultivation, hydroponics and preventive pest exclusion measures enables the intensification of high-value, nutritious fresh vegetable production, with a reduced need for pest control.

Research and commercial practices demonstrate that hydroponic production of lettuces and tomatoes in a greenhouse can yield about ten times more than open field production in one year. This result must be set against an initial investment cost that is on average five times higher. The opportunity to optimize resources such as space, water and fertilizers needs to be factored in according to each specific context (Lages *et al*., 2015; Fayezizadeh *et al*., 2021; Wang *et al*., 2023).

Vertical farming

An agricultural technique developed to mass-produce fresh vegetables – primarily leafy greens such as lettuce, herbs and sprouts – vertical farming employs controlled-environment agriculture technology to optimize plant growth by regulating temperature, light, water and nutrients (Butturini and Marcelis, 2020). These farms are called "vertical" because they stack multiple horizontal layers of growing beds and lamps on top of each other, significantly increasing plant density per unit area.

While ideally housed in industrial hangars, vertical farms can also be integrated into pre-existing structures such as buildings, underground areas, basements or shipping containers. This characteristic allows the creation of farms wherever they may be needed, making vertical farming particularly suitable for densely populated areas where demand for fresh and nutritious food is high, but the distribution of fresh food from rural areas presents logistical challenges (van Delden *et al*., 2021).

Vertical farms require significant capital, technology, inputs and skilled workers compared with conventional soil-based farming. They also demand energy to maintain optimal environmental conditions for high plant density and accelerated growth. For example, key elements such as air ventilation and intense lighting to sustain photosynthesis must be supplied for at least 12 to 16 hours per day (Beacham, Vickers and Monaghan, 2019).

To ensure economic sustainability, vertical farming typically focuses on a narrow range of high-end and high-value crops sold directly to end customers including supermarkets, hotels, restaurants, or individuals through digital platforms. Common produce from vertical farms includes lettuce, strawberries and microgreens (sprouts of cereals and pulses).

Rooftop farming

Rooftop agriculture, involving the cultivation of food, mostly vegetables, on the roofs of buildings and other existing urban infrastructure, offers an opportunity for efficient use of land in urban areas. This practice utilizes otherwise empty space to grow a variety of crops, employing techniques such as container gardening, hydroponics, aquaponics and raised-bed gardening. Container gardening is well-suited to rooftop agriculture, using pots and containers to grow plants such as vegetables. Hydroponics takes a soil-free approach, while aquaponics integrates fish farming with hydroponics, using fish waste as nutrients for plants and creating a symbiotic ecosystem. Raised-bed gardening involves the construction of soil beds on rooftops, applying traditional gardening methods adapted to urban environments.

The benefits of rooftop agriculture are multifaceted. It enhances local food supply and reduces dependency on distant food sources, thereby minimizing carbon emissions associated with food transport. Moreover, rooftop gardens mitigate the urban heat island effect by reducing surface temperatures, improving air quality and helping to manage stormwater runoff.

Despite its advantages, rooftop agriculture presents challenges. Structural limitations in buildings may impose weight restrictions on essential infrastructure, necessitating careful structural assessments and potential modifications. The initial costs of establishing rooftop gardens, including waterproofing, soil, containers and irrigation systems, can be substantial. Additionally, rooftop gardens are exposed to harsh environmental conditions such as wind, heat and heavy rain, which can impact crop yields and necessitate protective measures.

Globally, rooftop agriculture is gaining momentum, particularly in densely populated urban centres where land scarcity drives innovation. In Northern America, cities including Chicago and New York host notable rooftop farms such as Brooklyn Grange,[i] operating expansive soil-based farms across multiple rooftops. In Europe, initiatives such as Paris's Parisculteur,[j] aimed at greening rooftops and walls with vegetation, emphasize the important role of urban agriculture. Asian cities including Singapore and Tokyo showcase pioneering projects such as ComCrop,[k] responding to urban space constraints with innovative farming solutions. ■

TECHNICAL OPTIONS FOR PASTURELAND AND FEED PRODUCTION

There are about 656 Mha of pastureland around the world and they are frequently impacted by drought conditions (FAO, 2020b). Technical interventions aimed at improving water management and availability on pasturelands are essential for enhancing the overall health and functionality of pasture systems.

Feed crops represent 43 percent of all crops produced and the options for improving land- and water-use efficiency for those crops are no different from the interventions available for crops in general. Around 14 percent of the 3 670 km^3 of freshwater withdrawn each year for the irrigation of crops and pasture is allocated to produce feed items for livestock (Wisser *et al.*, 2024). Water for feed processing represents a small proportion of total water use and is typically neglected in water-use assessments (Pahlow *et al.*, 2015).

Broadly, interventions to improve pastureland and feed production can be subdivided into measures that enhance productivity and sustainability through species selection and measures that seek to reduce grazing pressure by managing grazing practices.

i For details, see: https://www.brooklyngrangefarm.com

j For details, see: https://www.parisculteurs.paris/en

k For details, see: https://comcrop.com

BOX 10 SOIL AND WATER MANAGEMENT IN PASTURELANDS OF CHINA

On the Qinghai-Tibet Plateau of China, soil-water storage in degraded grasslands improved by 41.9 percent from 2012 to 2018 through increased biomass input, litter and vegetation cover (Guo *et al*., 2021).

In the arid conditions of grazed dairy pastures in northwest China, studies have shown that the application of irrigation and nitrogen – and their interaction – significantly influence alfalfa forage yield, water-use efficiency and nitrogen-use efficiency. It has been demonstrated that 450 mm of irrigation combined with 150 kg of nitrogen per hectare yield the most favourable outcomes: optimal forage output, improved forage nutritional qualities, and increased resource-use efficiency of alfalfa (Kamran *et al*., 2022).

Pasture improvement and rehabilitation

Improving soil and water management in pasturelands

Increasing soil organic matter – and therefore the amount of carbon in the soil – significantly reduces soil erosion and enhances water infiltration by improving soil structural stability and water retention (Lai and Kumar, 2020). Soil organic matter enhances pasture resilience by supporting microbial decomposition, which supplies nitrogen to plants, and by improving water retention. Effective strategies such as incorporating cover crops during non-grazing periods enhance soil organic matter, wet aggregate stability and overall soil health (Shepherd, Nichols and Selbie, 2021; Stoner *et al.*, 2021). In arid regions, optimizing irrigation and nitrogen application is crucial for sustainable pasture systems (see Box 10). Specific combinations of irrigation and nitrogen levels can maximize forage yield, improve water-use efficiency and enhance forage quality (Kamran *et al.*, 2022).

Improving grazing practices

The impact of grazing intensity on soil's physical properties is significant. Heavy and moderate grazing increases soil compaction, bulk density and penetration resistance, which reduces water infiltration and depletes soil organic carbon and total nitrogen. Conversely, light grazing limits compaction while increasing organic carbon and nitrogen levels. Grassland root morphology plays a vital role in mitigating soil compaction and improving infiltration, especially in arid environments, highlighting the importance of soil management strategies to enhance water supply for sustainable forage production (Liu *et al.*, 2020).

Selection of drought-tolerant and water-efficient grass species

Perennial forage grass species offer specific advantages for high-quality livestock forage production. In comparison with most drought-sensitive annual species, perennial grass species can provide better water-use efficiency with fast regrowth at the start of autumn rains, more efficient use of residual soil moisture at the end of spring, and a reduction in the risk of soil erosion (Lelièvre and Volaire, 2009). Only a limited number of cultivars for perennial forage species adapted to arid climates are currently used in production systems. It is therefore recommended to use intraspecific and interspecific plant diversity to increase the drought resistance of permanent and sown productive grasslands (Lüscher *et al.*, 2022).

The selection of suitable grass species with high yield levels, drought tolerance and recovery capacity is essential to reduce drought stress, which can compromise forage productivity and ensure the survival of grass species, especially in arid and semi-arid regions. Optimal species and desirable genotypes for forage utilization, including *Festuca arundinacea*, *Lolium perenne* and *Lolium×hybridum*, were identified across various water conditions and geographical zones for prospective projects (Taleb *et al.*, 2023).

Integrating alternative forage and legumes

The integration of legumes contributes to the restoration of dryland pastures that can withstand harsh agroecological conditions and support high animal growth rates. The method consists of using drought-tolerant native forage legumes to rehabilitate degraded soils by covering the soil, fixing nitrogen, increasing water infiltration and preventing soil erosion (Smith and Elgersma, 2021). Water-use efficiency of native grassland is potentially enhanced by interseeding legumes. For instance, in the United States of America, alfalfa–grass mixtures produced 35 percent more forage mass and 96 percent greater nitrogen yield than grass alone, and reduced water-use competition with weeds (Dhakal *et al.*, 2020). On grazed pastures and nutrient-poor land on the Loess Plateau of China, a grass–legume mixture and nitrogen application significantly improved forage yield (by up to 44 percent) and water-use efficiency (by up to 52.5 percent) compared with monoculture and non-fertilized grasslands (Xu *et al.*, 2023).

The use of *Opuntia* spp. (cactus) as alternative feed has been suggested as added value to conventional feed due to its water conservation properties and nutritional quality (high content of minerals, proteins, dietary fibre and phytochemicals) (Pastorelli *et al.*, 2022). However, *Opuntia* should be carefully managed, as it can be an invasive species in some contexts.

Improved pasture management

Pasture management optimizes livestock production by providing animals with nutritious forage while maintaining soil health. This approach encompasses techniques to enhance grass growth, increase forage yield, support ecosystem balance and reduce production costs. Success in pasture management relies on understanding the interconnections between various components. For example, cattle grazing affects grass growth, which in turn influences weed presence, while water management plays a critical role in both environmental health and livestock well-being.

Improved grazing management

Livestock grazing management affects stream water quality, which is improved through integrated best management practices (BMPs) that consider hydraulic and geomorphic characteristics. In the southern humid region of the United States of America, BMPs include alternative water sources, exclusion fencing with riparian buffers, controlled grazing, improvement of forage availability with fertilizers and herbicides, and supplement feeding (Agouridis *et al.*, 2005).

Regenerative rotational grazing with extended resting periods facilitates uniform pasture utilization by cattle and mitigates the negative effects of both overgrazing and undergrazing. In the Basque Country of northern Spain, regenerative rotational grazing yielded a 30 percent increase in spring grass production and a 3.6 percent higher level of topsoil carbon storage compared with conventional rotational grazing, while improving water flow regulation (Díaz De Otálora *et al.*, 2021).

Rotational grazing can mitigate trade-offs between livestock production and water quality in semi-arid rangelands. Research conducted in northeastern Utah in the United States of America indicates that reducing grazing duration and shifting its timing are effective synergistic approaches: conflicts between livestock grazing and water quality are alleviated without the need to fence riparian zones or exclude cattle from pastures adjacent to streams. It should be noted, for example, that periods of high concentration of the bacterium *E. coli* in streams were determined by grazing periods (Hulvey, Mellon and Kleinhesselink, 2021).

On Canadian grassland soils, adaptive multi-paddock grazing – characterized by a very short grazing period at high stocking densities followed by an extended resting period – is considered beneficial to plant regeneration and has positive effects on hydrological processes through increased water infiltration (Döbert *et al.*, 2021).

An optimal grazing solution, which involves meticulous planning of animal units by area based on expected grass yields, must be combined with multifunctional agriculture and flexible land use (Centeri, 2022). The use of many paddocks per herd, together with adaptive stocking management, demonstrates reduced sensitivity to overstocking compared with fixed stocking (Teague and Kreuter, 2020).

BOX 11 PRECISION LIVESTOCK FARMING TECHNOLOGIES IN PASTURE-BASED SYSTEMS

- **Radio frequency identification (RFID) tags.** Each animal is fitted with an RFID tag to facilitate individual identification. This enables the tracking of lineage and monitoring of specific health parameters, including body condition and reproductive history.
- **Global positioning systems and accelerometers.** These devices are used to track animal movement patterns and detect anomalies in behaviour, such as reduced activity or increased restlessness, which can indicate health issues. The data are used to optimize pasture allocation and minimize overgrazing in specific areas.
- **Walk-over weighing platforms.** Farms install weighing platforms at strategic points (e.g. water troughs) to continuously monitor the weight of cattle and sheep. Coupled with automatic drafting systems, these platforms enable the sorting of animals based on weight changes, enabling early intervention if weight loss is detected.
- **Virtual fencing.** This innovative technology is used to manage grazing areas without the need for physical barriers. The system uses auditory cues followed by mild electrical stimuli to train animals to remain within designated zones. Advances in this technology present new opportunities for maximizing pastureland use while enhancing adaptability to changing pasture conditions and increasing precision and efficiency. However, further development is needed, particularly in reducing costs and enhancing efficiency across larger areas and with greater numbers of animals (Goliński *et al.*, 2022).
- **Remote sensing and unmanned aerial vehicles.** Satellite imagery and unmanned aerial vehicles are used to assess pasture biomass and estimate forage availability. The data are integrated with animal movement patterns to determine optimal stocking rates and identify areas at risk of overgrazing.

Precision livestock farming, pasture management and virtual fencing

Precision livestock farming (PLF) technologies are revolutionizing the management of pasture-based livestock systems by providing real-time individual animal monitoring and advanced decision-making capabilities (Aquilani *et al.*, 2022). The PLF approach integrates various technologies for real-time livestock monitoring, enhancing pasture utilization and animal management for cattle, sheep, goats, pigs and poultry (see Box 11). The main constraints when using these technologies include battery lifespan, transmission range, service coverage, storage capacity and affordability. Despite these challenges, PLF is expected to lead to positive outcomes in rangeland conservation, animal welfare and labour optimization (Aquilani *et al.*, 2022). ■

TECHNICAL OPTIONS FOR FORESTS AND THE RESTORATION OF DEGRADED LAND

Forests and trees, which cover 31 percent of the Earth's land surface, are essential components of agrifood systems (FAO, 2022a). However, their potential contribution to sustainable agrifood systems transformation remains undervalued. Forest conservation and sustainable use – recognizing the importance of communities as forest stewards – are essential to food security. For example, more than 50 000 wild species have been shown to support nearly half the world's population in terms of food security and livelihoods (Laird *et al.*, 2024). The restoration of degraded lands and agroforestry can help to support forest-based agrifood systems that tend to be more resilient to climate change than conventional agriculture (Ickowitz *et al.*, 2022). Building green value chains and better valuing non-wood forest products play an important role in the sustainable use of forests. This section highlights how such pathways can contribute to agrifood systems transformation and meet economic, social and environmental needs.

Halting deforestation and maintaining forests

Agricultural production can both drive deforestation and be negatively affected by it. The 2020 FAO Remote Sensing Survey of Forest Resources estimates that between 2000 and 2018, about 90 percent of global deforestation resulted from unsustainable agricultural expansion, of which some 50 percent was due to cropland expansion and 38 percent due to livestock grazing (FAO, 2022b). Additionally, in an analysis of 230 of the world's most important river basins, it was estimated that those that had lost more than 50 percent of their original tree cover (in 2015) faced medium to high erosion risk, forest fire risk and water stress (88 percent, 68 percent and 48 percent, respectively), which could have a direct impact on agricultural productivity (FAO, IUFRO and USDA, 2021).

Insufficient coordination among land-use sectors has consistently hindered efforts to harmonize forest-related and agricultural objectives at both landscape and national scales. Addressing complex challenges such as agriculture-driven deforestation requires innovative methods for integrated and spatial land-use planning and cross-sectoral multistakeholder collaboration. An example of such an integrated landscape approach is presented in Box 12.

Restoring degraded lands

Globally, unsustainable land-use management and practices, known as human-induced land degradation, affect 1 660 Mha (FAO, 2022c, 2024b). More than 60 percent of human-induced land degradation is on agricultural land (cropland and pastureland). This is impacting agrifood systems and food security, as well as the livelihoods of mainly those who directly depend on agriculture. However, there are considerable opportunities for reversing the trend through forest and landscape restoration (FLR), as well as the restoration of agricultural lands.

One example is the large-scale restoration of agrosilvopastoral lands for small-scale farming. In the Sahel, through its Action Against Desertification Programme, and in support of Africa's Great Green Wall initiative, FAO has been scaling up mechanized water harvesting, combined with the use of multiple local and adapted biodiversity (trees, shrubs and grasses) for food, feed and non-wood products, to restore hundreds of thousands of hectares of agrosilvopastoral systems in, among others, Burkina Faso, the Niger, Nigeria and Senegal (Sacande, Parfondry and Cicatiello, 2019). Between 2016 and 2020, Action Against Desertification implementing communities and partners in ten countries collected 120 tonnes of seeds from more than 110 native species and planted them, providing both ecological and economic benefits. Perceived food insecurity significantly declined in 2020 compared with 2016 observations, falling sharply from 46 to 15 percent at project sites in Senegal, from 69 to 58 percent in the Niger, and from 90 to 25 percent in Nigeria. In the Niger and Senegal, communities generated revenues from fodder species of USD 40/ha per year (Sacande and Muir, 2022).

Furthermore, the success of the Great Green Wall land restoration initiative was boosted through the use of symbiotic microorganisms inoculated in seeds and seedlings to improve land productivity and plant growth (Fofana *et al.*, 2020). A geospatial study estimated the contribution of Action Against Desertification to carbon sequestration at between 384 000 tonnes and 1.27 million tonnes of carbon sequestered (an increase of 2.2 to 9.3 percent from the baseline), for a median valuation of USD 3.9 million (2015–2020) (FAO, 2022d).

FAO has also partnered with multiple countries to implement forest and landscape restoration aimed at restoring ecological integrity and enhancing human well-being across degraded forest landscapes. Unlike simple tree planting, FLR focuses on revitalizing entire ecosystems to balance ecological, social and economic needs. Key principles include stakeholder engagement, local context adaptation and the promotion of multiple benefits, such as biodiversity conservation and improved land productivity. Examples of FLR in action include restoration of

BOX 12 APPLYING THE PARTICIPATORY INFORMED LANDSCAPE APPROACH IN NIGERIA

FAO's Participatory Informed Landscape Approach (PILA), developed under the Food Systems, Land Use and Restoration Impact Program of the Global Environment Facility (GEF-7), demonstrates how cross-sectoral coordination can drive tangible and resilient outcomes on the ground while minimizing trade-offs between forest conservation, ecosystem restoration and agricultural productivity. The approach is guided, structured and tailored, and leverages FAO's state-of-the-art tools and methodologies to support integrated landscape management (ILM) for transformative food systems.

With PILA, countries receive integrated technical support and expertise from diverse domains, including forestry, crop and livestock production, land and water resources, geomatics, transformative governance, tenure, finance and multistakeholder processes. All these components work in synergy, to address landscape management challenges in a single holistic approach.

The Participatory Informed Landscape Approach is currently being applied in Nigeria's Delta Region, where the cultivation of high-value crops such as cocoa and oil palm has resulted in severe environmental degradation, including deforestation and a decline in ecosystem services. To address these challenges, the technical and institutional capacities of national counterparts in Nigeria have been strengthened through, for example:

- **Tool for Agroecology Performance Evaluation (TAPE)** – a household and farm-level survey for measuring/monitoring the agroecology performance of farming systems across the multiple dimensions of sustainability.
- **Transformative governance** including tenure and integrated land-use planning – tools to enhance institutional frameworks and multistakeholder landscape governance.
- **The Economics of Ecosystem Restoration (TEER) Initiative** – an initiative supporting cost-effective restoration practices and monitoring the costs and effectiveness of restoration activities as agroforestry.
- **Geospatial approach** – tools supporting integrated geospatial analysis, incorporating reliable field and remotely sensed data, as well as mapping restoration potential and assessing land-use change dynamics.

Additionally, multistakeholder processes have been facilitated, engaging landscape participants – including governments, project partners and producer organizations – and bringing them together around a unified planning table. The anticipated outcome is the development of more inclusive, better informed and fit-for-purpose ILM plans that empower stakeholders to manage their landscapes in a holistic, sustainable and consensus-based manner.

the cork oak forest landscape in Maâmora and of the Atlas cedar forest landscapes in the Middle Atlas, both in Morocco (see Box 13).

Promoting agroforestry

Agroforestry, a collective term for land management practices where woody perennials are deliberately integrated and managed with agricultural crops and/or animals, is a good example of the synergies between trees and agriculture, whether implemented as tree management on farms or as farming in forest landscapes (Udawatta, Rankoth and Jose, 2019). It is estimated that 40 percent of global agricultural land has more than 10 percent tree cover, including a diversity of agroforestry systems that fulfil a variety of livelihood objectives while contributing to ecosystem functions (Zomer *et al.*, 2009).

As an integrated food system, agroforestry has the potential to advance global food security by increasing crop yield and resilience, improving livelihoods, providing ecosystem services and addressing land degradation. Of the more than 2 billion ha of degraded land identified as potentially available for restoration worldwide, 1.5 billion ha are considered best suited to mosaic restoration, where forests and trees are combined with other land uses, such as agriculture (Minnemeyere, Laestadius

BOX 13 FOREST AND LANDSCAPE RESTORATION IN MOROCCO

The FAO Forest and Landscape Restoration Mechanism has initiated a restoration project in Morocco focusing on the cork oak Maâmora forest and Atlas cedar ecosystems in the Ifrane region (Middle Atlas). The primary goal is to rehabilitate 5 000 ha of degraded forest through a participatory framework that actively involves Indigenous Peoples in all stages of planning, implementation and monitoring. This inclusive strategy ensures that restoration activities are aligned with local needs and leverage Indigenous Peoples' knowledge. A key component includes conducting baseline assessments on non-wood forest product value chains, with a particular focus on truffles, which enhance sustainable livelihoods for local populations.

The project also significantly impacts Morocco's climate strategy. In 2021, it contributed to an updated nationally determined contribution, emphasizing the importance of restoring degraded forests as part of national efforts to combat climate change. This revision positions the forestry sector at the forefront of Morocco's commitment to achieving a 45.5 percent reduction in greenhouse gas emissions by 2030.

and Sizer, 2011). Another study found that 1 billion ha of croplands and rural areas located on previous forestlands would benefit from the establishment of trees to increase agricultural productivity and from the provision of ecosystem services such as improved soil nutrient and water capacity and pest and weed management (Pumariño *et al.*, 2015).

It is estimated that agroforestry systems can contain 50 to 80 percent of the diversity of natural forests and may have 60 percent higher mean taxa richness than forests, consisting of both forest and non-forest species (Udawatta, Rankoth and Jose, 2019). This greater biodiversity includes above and below ground flora and fauna species, many of which – for example, pollinators, soil organisms and mycorrhizae – can increase agricultural productivity (FAO, 2022e). A global meta-analysis demonstrated that successfully restored agroecosystems, such as agroforestry systems, increased overall species biodiversity by an average of 68 percent and the supply of ecosystem services by 42 percent (Barral *et al.*, 2015). Agroforestry has been shown to reduce soil erosion to varying degrees across temperate, tropical and Mediterranean regions, as well as to enhance soil health characteristics such as microbial activity, organic matter and moisture content, and nutrient availability (Muchane *et al.*, 2020; Ngaba *et al.*, 2023). However, the potential of agroforestry systems to enhance regulating and provision ecosystem services like these is context-specific and dependent on a range of factors, including soil type, species, local knowledge, management techniques and capacity, topography and placement in the landscape, water availability, and climatic conditions (Barrios *et al.*, 2023).

Sustainably using forests and building green value chains: the role of non-wood forest products

According to *The State of the World's Forests* (FAO, 2022a), forests and trees can provide about 20 percent of the income of rural households in developing countries; non-timber forest products provide food, income and nutritional diversity to approximately 20 percent of the world population, especially women, children and other people in vulnerable conditions. Much of the daily diet of rural families comes directly from these products including fruits, tubers, vines, fungi and legumes, as well as insects and animals.

It is important to emphasize the role of family farming as an integrated system where the sustainable use of forests and subsistence crops coexists. It is therefore critical to strengthen value chains and markets for the responsible consumption of certain promising products, through which Indigenous Peoples could improve their livelihoods, while recognizing

BOX 14 SCALING OUT GREEN VALUE CHAINS: THE SUSTAINABLE LANDSCAPE PRODUCTION FRAMEWORK

The Sustainable Landscape Production Framework (SLPF), developed under the GEF-7 Sustainable Forest Management Impact Program on Dryland Sustainable Landscapes (DSL-IP), integrates three complementary pillars – climate-smart business (CSB), the Forest and Farm Facility (FFF) and Farmer Field Schools (FFS) – to address the interconnected social, environmental and economic dimensions of landscape management. By promoting a systems thinking approach, the SLPF links forest conservation with sustainable agriculture and value chain development.

To identify key barriers to resilience, the DSL-IP implemented in five country projects a household survey using the Self-evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists (SHARP+) tool combined with a behavioural change analysis. This approach aimed to assess vulnerabilities within agroecosystems and gain a deeper understanding of farmers' practices and decision-making, in order to design sustainable interventions for the long term.

Climate-smart business enhances resilience by preserving locally adapted drought-tolerant crop and forest species, supporting genetic diversity and reducing reliance on external inputs. The Forest and Farm Facility builds sustainable livelihoods by improving the capacities of producer organizations in business development, ensuring economic and social benefits while protecting forest ecosystems. Farmer Field Schools deliver hands-on training in sustainable land and forest management, combining technical skills with peer learning to empower communities and leverage existing knowledge.

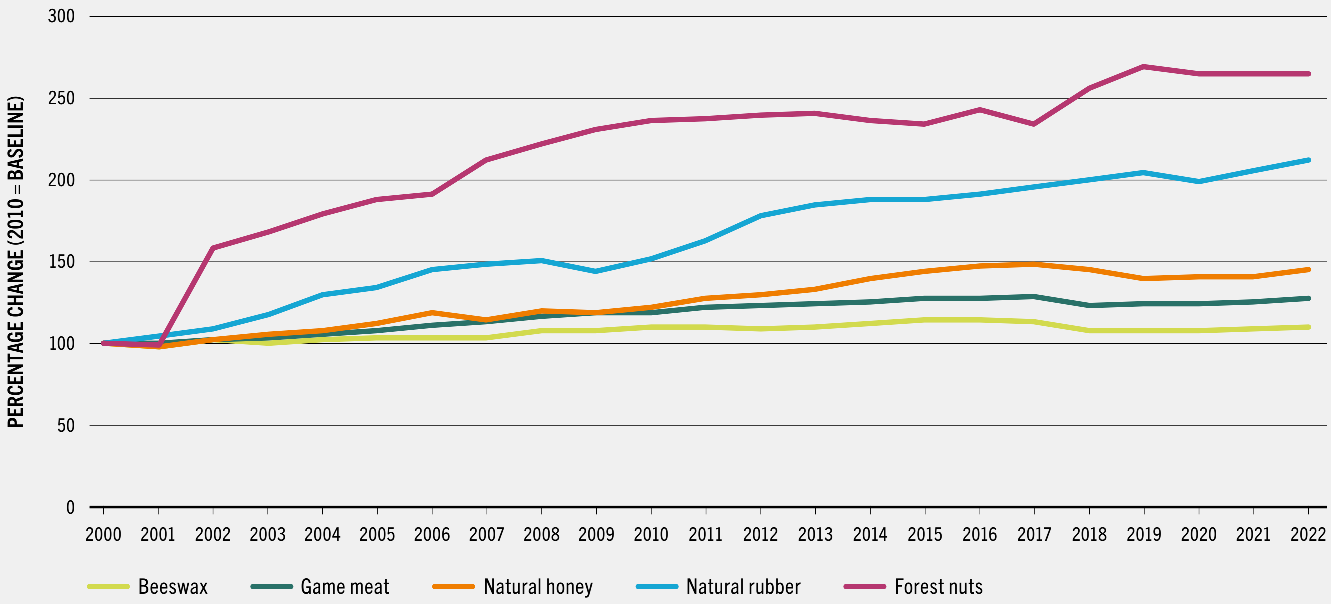
In the DSL-IP country project in Malawi, the SLPF supports the scaling out of an integrated food and energy systems approach, centred on intercropping with pigeon pea. Pigeon pea, a drought-tolerant legume, provides multiple benefits. Its stems serve as fuel, reducing household reliance on wood extraction and alleviating pressure on forest resources, while its pulses improve food security and nutrition. Additionally, pigeon pea enhances soil fertility through nitrogen fixation, supporting soil health and agricultural productivity. The SHARP+ and behavioural change analysis revealed that 68 percent of farmers in the project landscape had cultivated pigeon pea in the previous 12 months. These farmers reported benefits such as increased income, improved household nutrition, higher yields and enhanced soil fertility. The major challenges for pigeon pea growers are limited markets and access to quality seeds (FAO, 2025b). The SLPF creates the enabling environment for this practice by integrating CSBs to conserve and distribute pigeon pea varieties (alongside tree seedlings), FFF initiatives to build market linkages for pigeon pea products, and FFS to provide hands-on training in pigeon pea cultivation, intercropping and sustainable land/forest management.

their traditional knowledge. Box 14 provides an example of an innovative approach to enhancing green value chains.

Forest wildlife can also be a significant source of wild meat. For example, in the Congo Basin, consumption of wild meat reaches 5 million tonnes per year and in the Amazon Basin, up to 1.3 million tonnes are consumed annually, providing up to 80 percent of the daily protein needs of local people (FAO, 2022a). Research has shown evidence of the positive linkages between forests, trees and wild products, with nutritious and diverse diets making forest-based agrifood systems crucial to food security (Muir *et al.*, 2020).

However, the current and future economic value of NWFPs and their contributions to local livelihoods and nutrition have gone largely unnoticed due to lack of data and monitoring. The integration of NWFPs in national forest inventories can help to understand their use and economic potential; at present, obtaining geographically representative data on NWFPs, especially in the food category, remains challenging (Laird *et al.*, 2024). FAO analysed trends in NWFPs for beeswax, game meat, natural honey, forest nuts and natural rubber, with forest nuts showing a 165 percent increase in production between 2000 and 2022, the highest increase of all the products assessed (see Figure 26; FAO, 2024c). Improvements in the availability of data on

FIGURE 26 **TRENDS IN PRODUCTION OF FIVE NON-WOOD FOREST PRODUCTS, 2000–2022**



SOURCES: FAO. 2024. *The State of the World's Forests 2024 – Forest-sector innovations towards a more sustainable future*. Rome. https://doi.org/10.4060/cd1211en; FAO. 2023. FAOSTAT: Crops and Livestock Products. [Accessed on 29 December 2023]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

https://doi.org/10.4060/cd1211en-fig03

NWFPs such as pine nuts, forest mushrooms and truffles are also leading to a better understanding of their high market value, which reached USD 1.8 billion in 2022 (FAO, 2024c). For the potential of NWFPs to be realized, factors such as resource availability, land tenure, market access and cultural practices need to be addressed and prioritized (Laird *et al.*, 2024). ■

TECHNICAL OPTIONS FOR INLAND FISHERIES AND AQUACULTURE

Inland fisheries account for more than 12 percent of global fish production from less than 1 percent of the available aquatic habitat. In 2021, inland capture fisheries provided 11.4 million tonnes of fish, with 90 percent used for human consumption (FAO and AfDB, 2024). More than 20 percent of production originates in low-income and food-deficit countries, where fish serves as a vital source of nutrition. Fish delivers essential proteins, omega-3 fatty acids, vitamins and minerals that are fundamental to human health and offer a higher density of bioavailable nutrients (FAO, 2024a).

Around 99 percent of inland capture fisheries production comes from small-scale fisheries (FAO, Duke University and WorldFish, 2023), often integrated into agricultural landscapes such as reservoirs, canals and rice fields. For instance, the Tonle Sap Lake fishery in Cambodia is one of the world's most productive inland small-scale fisheries, supporting more than 200 fish species and millions of livelihoods through its seasonal flood-pulse system.

BOX 15 NATIONAL PLAN OF ACTION FOR SUSTAINABLE SMALL-SCALE FISHERIES IN UGANDA

In Uganda, the National Plan of Action for Sustainable Small-Scale Fisheries (NPOA-SSF) was launched in August 2023 to implement the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication. Small-scale inland fisheries play a critical role in Uganda's economy, providing food for 15 million people and livelihoods for 5.3 million. The NPOA-SSF focuses on increasing visibility and empowering small-scale fishers by recognizing human rights, organizing governance systems, promoting socioeconomic development and managing the health of fish habitats. The objectives include managing fish habitats by addressing land-use changes and controlling pollution and invasive species (MAAIF, 2023).

To ensure sustainable fisheries, the plan highlights the importance of applying lake productivity potential, sustaining and increasing fish production and providing essential support services such as capacity building and infrastructure. It aims to regulate fishing, reduce illegal activities and improve market systems, while combating the impacts of climate change. The NPOA-SSF aligns with Uganda's development agenda, contributing to key goals such as food security, poverty reduction and the sustainable management of fisheries through a five-year implementation strategy.

Aquaculture is the fastest-growing food production sector and provides important opportunities to increase the production of nutritious foods. Inland aquaculture has experienced significant growth, accounting for 62.6 percent of the total aquaculture production of aquatic animals in 2022 (FAO, 2024a). Almost 90 percent of inland aquaculture comes from freshwater finfish farming, such as carp (*Cyprinus* spp.), Nile tilapia (*Oreochromis* spp.) and catfish (Pangasiidae, Claridae). Asia, particularly China, and countries of South and Southeast Asia dominate aquaculture production, accounting for more than 91 percent of the world's inland aquaculture.

Promoting an ecosystem approach to inland fisheries and aquaculture

FAO promotes the ecosystem approach to fisheries (EAF) and the ecosystem approach to aquaculture (EAA) (FAO, 2019, 2021). These approaches seek to manage aquatic resources sustainably and emphasize the balance between ecological well-being, human well-being and good governance. Both EAF and EAA encourage adaptive management, stakeholder participation and precautionary principles to deal with uncertainties and environmental risks. Both approaches include the development of management plans that take account of issues affecting ecological and human well-being. These plans typically consider a range of species, have multiple objectives, address issues at appropriate spatial and temporal scales, utilize both scientific and traditional knowledge, and address the interactions between inland fisheries and other sectors (FAO, 2019).

The Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines) (FAO, 2015) highlight the role of small-scale fisheries and emphasize the need for equitable access to resources, secure tenure rights and governance systems that ensure their sustainability. Tenure is also a key focus area in broader frameworks, such as the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security (VGGT) (FAO, 2022f). By integrating fishers and fishery management in the VGGT, small-scale fishers are increasingly recognized as legitimate stakeholders in the management of shared natural resources, improving equity, coherence and sustainability across sectors such as land and water (see Box 15).

The Guidelines for Sustainable Aquaculture provide a comprehensive framework designed

BOX 16 INNOVATION IN INLAND AQUACULTURE

Methodological and technological innovations have modified the way that inland aquaculture is practised in many countries (FAO, 2024a). Earth ponds remain the most widespread method for raising finfish. Innovations in pond-based aquaculture focus on enhancing productivity and reducing environmental impacts. The in-pond raceway system, increasingly adopted in China and other Asian countries, confines the fish to "raceways" in a small portion of the pond, with the potential to double or triple production compared with traditional pond systems. Another example of innovation is cluster-based effluent treatment in fish farms, with constructed wetlands used as filters for water recycling.

BOX 17 INTEGRATING FISHERIES INTO IRRIGATION SYSTEMS IN KIRINDI OYA, SRI LANKA

The Kirindi Oya irrigation scheme in Sri Lanka is an example of the successful integration of fisheries into irrigation systems. Originally constructed for agricultural purposes, the large reservoirs in the system were modified to retain more water for extended periods, leading to increased fish production. These reservoirs now serve as fish habitats, boosting local fisheries and contributing to food security. Moreover, the storage systems are increasingly used for stocking fish as part of culture-based fisheries, enhancing food security for local communities. The modification of water retention practices has created a sustainable source of livelihood for local communities, illustrating how simple changes in irrigation management can result in significant benefits for both agriculture and fisheries (Gregory, Funge-Smith and Baumgartner, 2018).

to address the challenges associated with aquaculture's rapid growth and its impact on the environment and society (FAO, 2024d). Key areas include sustainable resource management, biodiversity conservation and social responsibility, with a focus on promoting decent work, gender equality and youth empowerment. The guidelines also emphasize efficient water use and reuse, recommending practices such as water recycling and nutrient recovery to minimize consumption, reduce pollution and enhance the sustainability of aquatic ecosystems (see Box 16).

Integrating fisheries and aquaculture in water and land management

Inland fisheries and aquaculture face significant threats from competition for water and land resources. Wetlands, floodplains and small waterbodies, which are some of the most productive environments for inland fisheries, are also the most vulnerable to agricultural expansion, water abstraction, drainage and other water infrastructures. For example, water stored in reservoirs for irrigation and hydropower can fragment river systems, disrupting fish migration and breeding cycles. Similarly, the canalization of rivers and the drainage of wetlands for farming significantly reduce fish habitats.

There is a need for much more integration of fisheries within irrigation system planning. Irrigation systems, traditionally designed for agriculture, can support fish production without compromising crop yields (Gregory, Funge-Smith and Baumgartner, 2018; Box 17).

Floodplain fisheries also offer significant potential for increased fish production, especially when managed effectively in conjunction with agriculture. Techniques such as cutting channels through levees to connect rivers with adjacent floodplains allow fish to migrate and spawn during flood seasons. Additionally, there is a need in the land and water management sectors to acknowledge the importance of connectivity and natural flow regimes such as the flood pulse. Flood pulses, which allow for the seasonal expansion and contraction of rivers, are critical for fish reproduction and habitat connectivity. Without this natural variability, fish species struggle and the population declines, even if water quality is maintained.

Improving connectivity within irrigation infrastructure is key to supporting sustainable fisheries. Barriers such as dams and weirs often obstruct fish movement, reducing fish habitat availability. However, modifications to irrigation infrastructure, such as installing fish-friendly structures like fishways, can help to mitigate these challenges (Gregory, Funge-Smith and Baumgartner, 2018).

Restoring degraded wetland ecosystems

Restoring degraded wetland ecosystems, such as freshwater lakes and floodplains, can play a key role in supporting inland fisheries and enhancing ecosystem services. Restoring fish habitats in modified landscapes, such as reservoirs and irrigation canals, is key to ensuring the sustainability of fish production (Coates, 2023). Ecosystem-based solutions, such as re-establishing natural water flows and restoring riparian habitats, not only boost fish production but also provide broader benefits, such as flood protection and improved water quality. In African and Asian floodplains, restoration efforts have successfully increased fish stocks and agricultural productivity, creating a win–win scenario for both sectors (Coates *et al.*, 2025).

The SSF Guidelines advocate ecosystem restoration as a means of securing the livelihoods of small-scale fishers while promoting biodiversity conservation. Incorporating these approaches into national and regional land and water management strategies can ensure that fisheries are sustained even in the face of increasing climate and development pressures (Coates, 2023). ■

TOWARDS INTEGRATED SOLUTIONS

This chapter emphasizes the interconnectedness of sustainable land, water, forest and aquatic resource management and highlights the complementary technical solutions proposed for each sector. Together, these strategies address challenges caused by water scarcity, soil degradation, deforestation and biodiversity loss. By integrating sectoral solutions, FAO advocates a holistic approach to resource management, one that aligns with the Organization's cohesive framework of transforming agrifood systems for better production, better nutrition, a better environment and a better life, leaving no one behind.

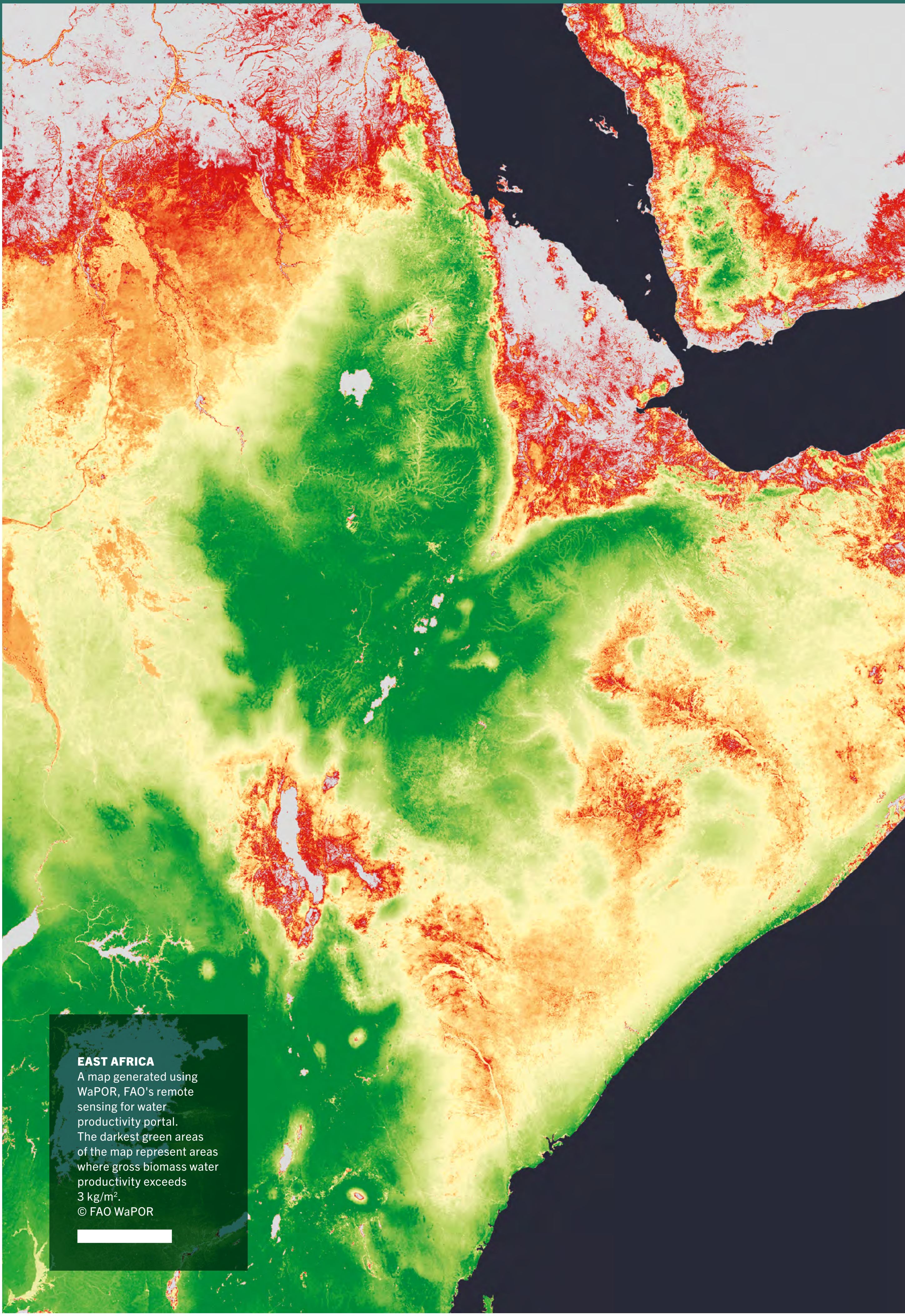
The practices of integrated plant production and forestry enhance soil health and restore degraded landscapes, both of which are essential to ensure long-term land productivity and adaptation to climate change. In rainfed agriculture, a focus on organic amendments, crop diversification and conservation tillage directly supports forest restoration efforts by fostering soil conditions that stabilize and enrich surrounding landscapes. Agroforestry systems, known for their resilience and rich biodiversity, complement these practices by providing long-term soil benefits, such as increased soil moisture retention and carbon sequestration. Together, these approaches create mutually reinforcing land-use practices that support both climate mitigation and ecosystem resilience.

Rotational grazing and forage improvement align with broader ecosystem strategies and support the health of both livestock systems and the natural environment. Integrating agroforestry practices within pasturelands can provide shade, improve forage quality and enhance soil health, while rotational grazing maintains productive grasslands that prevent soil erosion and loss of biodiversity. By encouraging the strategic inclusion of trees in grasslands, these complementary practices promote resilience to climate extremes, help to manage erosion and enhance carbon sequestration within pasture ecosystems.

The technical options for irrigation and inland fisheries illustrate how water resources can be jointly managed to support agriculture and fisheries, maximizing food production while conserving water. Designing and managing agricultural water for multiple uses – drinking water, industries, livestock and fisheries – can raise the social and economic productivity of water in water management systems (Jepson, Stellbauer and Thomson, 2023). Multifunctional farm ponds can store water for irrigation and domestic purposes and can be used for raising fish. Integrating agriculture with aquaculture provides a means of recycling water and nutrients and increasing income. The value of paddy cultivation is underestimated – unless its multifunctional roles are taken into consideration. By including fish-friendly irrigation infrastructure, irrigation systems can further enhance both aquatic biodiversity and food security without compromising agricultural productivity.

In all these sectors, the adoption of technical solutions requires community engagement, data-driven solutions and adaptive practices that consider both the environmental and the social dimensions of resource management. A case in point is the involvement of local communities in irrigation modernization, including monitoring and management, which has been shown to be essential to long-term outcomes. Data-driven insights and community involvement to adapt to local needs is a focus emphasized by the SSF Guidelines, which advocate sustainable fisheries through community-led management. Together, these technologies and community-centred practices create a framework in which sustainable resource use is tailored to specific landscapes and enhances community resilience to climate change.

Presenting a range of often synergistic technical solutions, this chapter offers a unified model for sustainable land, water, forest and aquatic resource management that addresses multiple aspects of food security, climate resilience and environmental sustainability. The complementary strategies outlined here offer a road map for decision-makers seeking to balance food production with ecosystem health, demonstrating that integrated management practices are essential to building resilient, sustainable and equitable food systems. ■



EAST AFRICA
A map generated using WaPOR, FAO's remote sensing for water productivity portal. The darkest green areas of the map represent areas where gross biomass water productivity exceeds 3 kg/m^2.
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CHAPTER 5
AN ENABLING ENVIRONMENT FOR SUSTAINABLE SOLUTIONS

KEY MESSAGES

➔ Sustainable and integrated solutions are required to face the food, climate, land, soil, water and biodiversity crises. The need for these solutions has been confirmed in recent international processes, with various calls for action and the setting of targets and commitments aimed at accelerating the achievement of the Sustainable Development Goals. Integrated land, soil and water solutions offer an enabling framework for countries to enhance their efforts towards addressing these intertwined crises in a holistic manner.

➔ The three Rio Conventions (Convention on Biological Diversity, United Nations Convention to Combat Desertification and United Nations Framework Convention on Climate Change [UNFCCC]) and their resolutions and decisions highlight the role of agrifood systems in tackling the interconnected triple challenges: ensuring food security and nutrition for a growing global population; supporting the livelihoods of hundreds of millions of farmers and others in the food supply chain; and achieving these goals while supporting sustainable management of the natural resources (land, soil and water) on which sustainable and diversified food production and livelihoods depend.

➔ An agrifood systems approach is essential, as reflected in various methodologies and tools. The agroecological approach focuses on protecting the ecosystem base on which agriculture depends, and the agrifoods systems approach aims to achieve all the SDGs.

➔ Coherence between sectoral policies is needed to maximize the gains associated with land and water management and address overlaps and trade-offs between competing or conflicting objectives.

➔ Integrated land-use planning is key to translate the systemic and integrated approaches on the ground. Moreover, it is necessary to strengthen institutions and regulatory frameworks, and ensure sustainable investment and financing.

➔ Integrated land-use planning enables informed decision-making at different levels to address challenges and competing demands. An evidence-based integrated planning process is essential to incorporate the needs and views of different sectors and stakeholders, considering emerging opportunities to enhance production in a sustainable manner. The nine-step FAO guidelines for integrated land-use planning aim to facilitate this process (FAO, forthcoming).

➔ An integrated landscape approach to land-use planning is vital. Field interventions can be defined together with those stakeholders who benefit from or are affected by the use of land and water resources. This will ensure that land users' and stakeholders' needs are fully reflected and that tools are in place to support land-use decisions from national to local level, while addressing power asymmetries and inclusivity by promoting responsible governance.

➔ Integrated water resources management (IWRM) is recommended to optimize the spatial and temporal allocation and use of water resources. This is crucial given that agriculture accounts for more than 70 percent of global freshwater withdrawals. Different needs must be met, taking into consideration quantity, quality and adequate timing. Furthermore, IWRM should go hand in hand with integrated land-use planning. The necessary trade-offs will be addressed by relevant institutions and stakeholders at relevant scales, such as at catchment or river basin, national, regional or international levels.

➔ The Water–Energy–Food–Ecosystems (WEFE) nexus approach acknowledges the interconnectedness between water, energy and food systems and their impact on ecosystems. The WEFE nexus enhances resilience, maximizes synergies and promotes the participation of stakeholders and the sustainability of agrifood systems.

➔ Institutional capacities and integrated systems of data, information, science and technologies must be set in place and strengthened to enable sustainable and integrated land, soil and water resources management and inform supportive and coherent policies.

➔ Rural development policies need to consider efficient and sustainable natural resources management, building resilience and diversifying production systems. A resilient rural economy is vital, and policies must aim to reconcile different land uses, demands and objectives.

➔ Tenure arrangements for land and water management often ignore smallholders and vulnerable groups and their legitimate claim to access these resources. Securing access for smallholders and vulnerable groups offers the potential to enhance productivity, protect resources and contribute to inclusive rural development.

➔ Data and information are key to ensuring the sustainable and productive management of land and water. The rapid development of information and communication technologies, including remote sensing, offers new opportunities for supporting land and water management. Efforts should be made to ensure that the right type of information reaches the different decision-makers at all levels, and on time.

➔ Regulatory frameworks are essential to create a more conducive environment for clarifying land and water rights, and supporting the sustainable management of natural resources and, in turn, public and private sector investment. Too often, unclear environmental regulations, compounded by weak enforcement, exacerbate existing challenges. Stronger policies to promote sustainable land, soil and water management should include clear land and water rights, incentives for sustainable practices and disincentives for unsustainable ones.

➔ Most traditional agricultural investment fails to capture the environmental and social costs and benefits associated with agricultural production. Public and private investment instruments that increase agricultural productivity, contribute to inclusive development and preserve natural resources need to be developed and put in practice; at the same time, harmful incentives and subsidies should be reduced and repurposed. Sustainable investments require coordinated collaboration between the public sector and the financial and private sectors.

➔ Farmers, especially in developing regions, often lack access to the necessary technologies, information and skills required to implement sustainable practices. This knowledge gap hinders the adoption of innovative and sustainable land and water management approaches and techniques. Farmer-centred training and extension programmes should be institutionalized and use modern communication technologies to promote the adoption of sustainable practices that strengthen resilience, while ensuring the overall improvement of farmers' socioeconomic status.

➔ Farmers need to be recognized as agents of change. Their participation must be strengthened, ensuring that they are involved in the design of local solutions, and supporting their meaningful contribution in policy dialogue at all levels.

➔ Partnerships should be forged at different levels, from local to national, regional and international, to avoid duplication and enhance synergies and complementarities.

The previous chapters provide information about the potential to increase production and call for an enabling environment that should be enhanced to realize these options in practice. Thus far, the report has shown how, over the past decades, agriculture has responded to the rapidly increasing demand for food and other agricultural products. It has also stressed how these achievements have come at a heavy cost, both environmentally and in terms of resilience and inclusiveness. Land degradation, loss of biodiversity, increasing water stress and agriculture's contribution to GHG emissions are putting production systems at risk, while competition for increasingly scarce land and water resources have disproportionally affected the most vulnerable populations who depend on them for their food security and livelihoods (Meybeck *et al*., 2024).

Chapter 4 showcased some examples of technical solutions, demonstrating how they are implemented in different contexts for more sustainable and inclusive management of land and water resources, while ensuring sufficient food production. If such solutions are to be adopted in the long term by billions of land and water users around the world, including farmers, herders, fisherfolk and forest dwellers, a series of enabling conditions must be put in place and made operational.

The transition to sustainable land and water management requires coordinated efforts by governments, financial institutions and the private sector to provide the necessary support to farmers. By leveraging key drivers in order to address the constraints to implementation, it is possible to scale up interventions that can not only enhance agricultural productivity but also preserve the natural resources on which future generations depend. The pathway to a sustainable future lies in fostering an enabling environment that supports integrated, inclusive and forward-looking action for land, soil and water resources.

The following sections discuss some of the most important drivers to make this happen. They are grouped into levers (the integrated approaches that provide the technical background for developing and managing agrifood systems) and enablers (for scaling up sustainable land and water resources management). ■

LEVERS: INTEGRATED APPROACHES

Integrated approaches provide guidance for the effective, practical and coherent management of the interactions between different components of a system. They offer processes that seek to minimize any negative impact and maximize the expected benefits from social, economic and environmental perspectives. In agrifood systems, integrated approaches take into account the different facets of agriculture, since they are interrelated. The value of a system's approach is explained in the following sections, which cover the interactions related to land, soil, water, agroecology and energy, among others, highlighting the importance of taking into account the needs of farmers and other stakeholders.

Lever 1: Integrated land-use planning

The ever-rising demand for food, feed and fibre, as well as competing demands from urbanization and other economic sectors, place increasing pressure on land and water resources. Land use is a function of four interrelated thematic spheres: landscape, markets, social norms and legislation. Each of the four spheres interacts with the others to generate a particular land-use pattern in a given territory or landscape. This implies that in order to enact necessary or desirable changes in land use, planning must anticipate the consequent changes that will be needed in one or more of the spheres that work together to form the land-use pattern. An evidence-based integrated planning process is essential, supported by suitable tools and practices that incorporate the needs and views of different sectors and stakeholders, emerging opportunities and challenges.

Land evaluation systems and tools help to better match land use with its sustainable potential in order to reduce the amount of land required to meet human needs, minimize land degradation and cost-effectively restore already degraded lands (UNEP, 2016).

Integrated land-use planning and territorial planning offer a suite of tools to balance competing land-use demands and allocate resources across multiple users, sectors and

BOX 18 MAIN FEATURES OF INTEGRATED LAND-USE PLANNING (ILUP)

- Aims to enhance the sustainability of land use and management with the full participation of stakeholders.
- Assesses the prevailing biophysical, socioeconomic and legal conditions, drawing on multidisciplinary, multisectoral and local expertise to optimize land use across different parts of the landscape.
- Offers an approach to planning, taking into account that each situation is unique and demands its own solutions.
- Results in a negotiated outcome that needs to be implemented, evaluated and monitored.

SOURCE: Ziadat, F., Berkat, O., Ouchna, R., Touami, M., Fetsi, T. Harari, N., Mekdaschi Studer, R. & Schlingloff, S. 2022. Participatory land resources planning to promote sustainable landscape management in rainfed areas – Morocco. *Frontiers in Sustainable Food Systems*, 6. https://doi.org/10.3389/fsufs.2022.848043

BOX 19 MOROCCO: DEVELOPING A TERRITORIAL PLANNING PACT IN THE SOUSS-MASSA REGION

In Morocco, analyses were carried out to assess the types, degree and severity of land degradation "hotspots", as well as "bright spots", using FAO's Land Degradation Assessment in Drylands (LADA) and World Overview of Conservation Approaches and Technologies (WOCAT) tools. The analyses helped to identify appropriate technological solutions for sustainable land management (SLM). Results from local assessments were used to implement a process of participatory land-use planning in selected communities of the Souss-Massa region. The process led to the development of a Territorial Planning Pact for land-use planning and a three-year action plan to help implement and mainstream SLM in selected communities. The pact forms a base for the planning development programme in the region, with the involvement of key stakeholders. This example highlights the importance of integrating biophysical and socioeconomic information as part of a participatory process to identify the actions and responsibilities of various stakeholders and ensure both the sustainable management of scarce natural resources and improved livelihoods.

SOURCE: Ziadat, F., Berkat, O., Ouchna, R., Touami, M., Fetsi, T. Harari, N., Mekdaschi Studer, R. & Schlingloff, S. 2022. Participatory land resources planning to promote sustainable landscape management in rainfed areas - Morocco. *Frontiers in Sustainable Food Systems*, 6. https://doi.org/10.3389/fsufs.2022.848043

jurisdictions along an urban–rural continuum (UNCCD, 2023). The term "integrated" refers to recent trends in land-use planning: optimization of land and water use across different planning scales, participation by and consultation with stakeholders, multidisciplinary technical support, coordination with multiple sectors at different decision-making levels and the use of multiple tools. Modern approaches to ILUP are based on the principles of decentralization and participation, whereby the primary land users such as farmers, herders, fisherfolk or forest dwellers have a legitimate stake in the planning process, along with the actors who use the land for different purposes (e.g. settlements, sources of energy, industry, mineral resources, recreation and tourism). Increasing recognition is given to inclusiveness, taking account of the

TABLE 11 NINE STEPS IN THE FAO GUIDELINES FOR INTEGRATED LAND-USE PLANNING

Step	Description
Step 1: Initiate the integrated land-use planning process	Identify the area and decide on the goals and approach of the planning exercise. Determine characteristics, problems and the people involved.
Step 2: Perform stakeholder mapping	Ensure that all stakeholders at the relevant levels are identified. Analyse their characteristics, concerns and the anticipated benefits or losses they will experience from land-use changes. Pay special attention to land tenure and inequality issues, as well as to people who have legitimate tenure rights, whether they own land or depend on common property resources and ecosystem services.
Step 3: Establish a multidisciplinary taskforce	Ensure that adequate technical expertise and all stakeholder groups, particularly local actors, are represented on the taskforce. Prepare terms of reference, ensure access to necessary information and communicate their powers and authority.
Step 4: Characterize the land, its uses and users	Describe the distinctive environmental and socioeconomic features of the planning area, including land-use and user categories. Compile data using methods that are appropriate to each planning level.
Step 5: Undertake integrated analysis of land-use options	Assess the environmental, economic and social impacts of different land-use options for land users and their communities, with particular reference to women, young people, Indigenous Peoples and vulnerable groups. List the consequences, both positive (opportunity) and negative (impact), of different courses of action, considering issues of sustainability and equity.
Step 6: Consult and decide on suitable and acceptable land-use options	Hold public and executive discussions on the options and their consequences, based on the appraisal undertaken in Step 5. Decide which land-use changes to undertake using inclusive and participatory approaches.
Step 7: Prepare the integrated land-use plan	Allocate the selected land uses to target areas. Make plans for appropriate land management and determine how the land-use plan is to be put into practice. Prepare a budget and identify available financial resources. Communicate the decision to all stakeholders.
Step 8: Implement the integrated land-use plan	Employ a specific development project. Ensure that the implementation team works in close consultation with the target stakeholders.
Step 9: Monitor and evaluate the integrated land-use plan	Monitor the progress of the plan towards meeting its goals. Revise the plan as necessary, with the adequate engagement of all stakeholders.

SOURCE: FAO. (forthcoming). *Guidelines for integrated land-use planning – an update*. Rome.

specific needs of men and women, and vulnerable and marginalized persons from different socioeconomic and ethnic groups (see Box 18).

Integrated land-use planning uses participatory approaches that empower stakeholders to analyse an existing situation and enable them to propose the necessary changes and develop an agreed plan. This calls for land users to be given a central role, since their intimate knowledge and experience of their own territory places them in the best position to articulate their needs and desires for change (see Box 19) (Ziadat *et al.*, 2022).

Integrated land-use planning considers the following issues: climate change, land degradation neutrality (LDN) and restoration, conservation and sustainable use of biodiversity, urbanization, peri-urban and urban agriculture, governance, land and water tenure, and the rights of women and Indigenous Peoples. FAO is in the process of updating the guidelines on ILUP based on nine steps (see Table 11 and Figure 27).

Lever 2: Integrated landscape management

Integrated landscape management is the basis of natural resource management; it ensures that, by managing the natural resource base and ecosystem services through a coordinated process across sectors and stakeholders, the full range of societal needs can be met in the short and long term (FAO, 2017a).

FIGURE 27 THE NINE STEPS OF THE FAO GUIDELINES FOR INTEGRATED LAND-USE PLANNING

SOURCE: Adapted from FAO. (forthcoming). *Guidelines for integrated land-use planning – an update*. Rome.

Diverse landscape management approaches have been developed from different entry points but aim at realizing multiple outcomes simultaneously. Commonalities include generating an agreed vision among stakeholders of long-term and wide-scale landscape goals; adopting a mosaic of practices that achieve multiple objectives; devising strategies to manage spatial interactions across different land uses and users; establishing institutions for stakeholder dialogue, negotiation and action; and shaping markets and policies to support desired outcomes. These processes cover the technical, socioeconomic, market and policy dimensions and are mutually reinforcing (LPFN, 2015).

Up-to-date land-use planning tools have strong potential to support integrated landscape management and land restoration processes. Field programmes should be designed and implemented in a range of countries to validate the utility of updated tools and to fine-tune them to ensure that user needs are fully reflected and that tools are in place to support land-use decisions at national to local scales (FAO, 2017a).

BOX 20 MAKING INTEGRATED WATER RESOURCES MANAGEMENT WORK FOR FISHERIES

To reconcile the needs of inland fisheries with agricultural demands, adopting integrated water resources management (IWRM) is essential, as it facilitates cross-sector collaboration among fisheries managers, farmers and other water resource planners, ensuring that fisheries are considered part of the broader basin planning and management.

Assessing inland fisheries at basin scale is critical for understanding and managing the threats that they face. Basin-level assessments offer a comprehensive view of various factors impacting fisheries, such as habitat degradation, water pollution and overfishing (FAO and AfDB, 2024). Basin assessments can therefore play a crucial role in promoting IWRM by providing valuable insights into the productivity and health of inland fisheries, helping stakeholders to make informed decisions regarding water use and allocation.

Inland aquaculture presents another opportunity for integrated food production. Rice–fish farming systems are a prime example, where fish raised in flooded rice fields contribute both to farm incomes and nutrition, while simultaneously utilizing water more efficiently. Additionally, using nutrient-rich aquaculture water to irrigate crops can improve overall ecosystem productivity.

Finally, effective governance is critical to achieving sustainable outcomes in land and water management. Various policy frameworks (such as the Guidelines for Sustainable Aquaculture, the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication, and the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests) emphasize the need for participatory governance, where small-scale fishers and aquaculture producers are actively involved in managing the resources on which they depend. Co-management approaches, which empower local communities to participate in decision-making processes, can help to balance the needs of different sectors and promote the sustainable use of aquatic ecosystems.

Lever 3: Integrated water resources management

Integrated water resources management (IWRM) is defined as "a process that promotes the coordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Agarwal *et al.*, 2000, p. 6).

Adopting an IWRM approach is recommended to optimize the spatial and temporal allocation of water resources for different water quantity and quality needs. Such needs may be, for example, for crop varieties with their own cyclical – mostly seasonal – requirements, fisheries and aquaculture, livestock, and other non-agricultural sectors such as domestic water supply, energy, industry and recreation.

Given that agriculture accounts for more than 70 percent or freshwater abstractions, the sector plays a critical role in IWRM. Reducing inefficiencies makes it possible to produce more food (more crops per drop) and free more water for subsectors within agriculture and for other sectors; in addition, it ensures a more equitable sharing of water between different users, correcting past inequities in some instances. Integrated water resources management can also ensure the allocation of water for crops that are more nutritious and, where relevant, crops that give a higher economic return.

Integrated water resources management should be implemented hand in hand and in complementarity with integrated land-use planning. It fosters the establishment of institutional arrangements that will oversee equitable sharing of the socioeconomic and environmental benefits, taking into account upstream and downstream water demands at the scale of a catchment at local, national, regional or international levels, such as in shared river basins (see Box 20).

Lever 4: Water–Energy–Food–Ecosystems nexus

The Water–Energy–Food–Ecosystems (WEFE) nexus approach acknowledges the interconnection between water, energy, food and ecosystems. Water is essential for the production of energy such as hydropower and the cooling of coal-fired or nuclear power stations; energy is critical for accessing and distributing water; both water and energy are important in food systems, at different levels of the value chain, from production, transformation and commercialization to consumption. Food systems also have an impact on water and energy in different ways. For example, water used for agriculture may not be available for energy or other sectors and may result in water pollution.

Ultimately, any development linked to water, energy and food systems will have an impact on the ecosystems that provide the natural resource base on which it relies. A WEFE nexus approach therefore stresses the critical importance of ecosystems and includes: i) assessment of opportunities for maximizing synergies between the three components, achieving efficiencies and reducing any risk; ii) development of appropriate responses; and iii) implementation of the required practical solutions on the ground, in a participatory manner.

Understanding these key interactions, and the potential synergies and trade-offs between water resources, energy generation, food production and ecosystems, is critical to addressing growing societal demands in a context of climate change, increasing biodiversity loss and pollution.

The WEFE nexus is an efficient approach that enhances the resilience and sustainability of agrifood systems. It advances policy coherence and supports an integrated and coordinated approach across the four sectors, with a view to reconciling conflicting interests. FAO's mandate to achieve food security serves as an entry point for its work on the WEFE nexus.

Lever 5: Agroecology

Agroecology has been defined as "the integration of research, education, action and change that brings sustainability to all parts of the food system: ecological, economic, and social" (Gliessman, 2007). Agroecology is transdisciplinary, in that it values all forms of knowledge and experience in food systems change. It is participatory, in that it requires the involvement of all stakeholders from the farm to the table and everyone in between. And it is action-oriented, because it confronts the economic and political power structures of the current industrial food system with alternative social structures and policy action. The approach is grounded in ecological thinking, where a holistic, systems-level understanding of food systems sustainability is required (Gliessman, 2018).

As in the definition, agroecology seeks to achieve a balance between three dimensions (ecological, economic and social) by integrating various disciplines that have an impact on food systems in a participatory manner, leading to the required actions in the face of competing pressures from economic and political structures, with the underlying prioritization of ecological integrity and sustainability (Tittonell, 2023).

While agroecology might not meet with a general consensus, it emphasizes that all stakeholders share the responsibility of ensuring that the integrity of ecosystems is not compromised by agriculture, highlighting the importance of locally driven solutions for sustainable agrifood systems.

Lever 6: Agrifood systems approach

Agrifood systems encompass the entire range of actors and their interlinked value-adding activities in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture, forestry or fisheries, and parts of the broader economic, societal and natural environments in which they are embedded. Agrifood systems are composed of subsystems (e.g. farming, waste management and input supply systems) and interact with other key systems (e.g. energy, trade and health systems); they also interact with and depend on other interrelated systems such as water and land systems (FAO, 2025a). Therefore, a structural change in a food system may originate from a change in another system; for example, a policy promoting more biofuel in the energy system will have a significant impact on food systems (FAO, 2018).

Thus, in an agrifood systems approach, the interaction of each agricultural commodity with all other systems at the various steps in the value chain is considered with the aim of achieving food security and nutrition without compromising the economic, social and environmental bases on which it depends, for the needs of present and future generations. With the objective of contributing to the achievement of the Sustainable Development Goals, a sustainable food system may need to be assessed and redesigned in order to contribute to sustainable production, inclusivity, sustainability, resilience, nutrition and healthy diets, requiring different kinds of interventions (from policy to field actions) at different levels and from different role players. ■

ENABLERS: SCALING UP SUSTAINABLE LAND AND WATER RESOURCES MANAGEMENT

Enabler 1: Policy coherence across sectors

For the assessment of policy coherence, a range of methodological approaches exist, such as scoring and ranking, trade-offs assessment, and quantitative modelling across policy priorities and planned actions. Different methods and mechanisms can be used to facilitate policy coherence and cross-sectoral coordination, including establishing a high-level committee or a coordinated institutional mechanism; building formal or informal partnerships and processes for sharing and learning across sectors and actors; aligning incentives; and conducting simulation and mapping exercises, integrated, multistakeholder consultations and strategic impact assessments.

While these methods often describe a "staged" approach to policy coherence and joint cross-sectoral planning, the reality of policymaking is often a more chaotic process, comprising a wide range of inputs, values and priorities that are both internal and external to the government and require mediation, negotiation and brokering. It is therefore essential to apply a flexible, inclusive and analytical approach that is adapted to the specific national, institutional and historical socioeconomic and political context. In addition, it is necessary to establish innovative governance mechanisms and promote measures for coherence and cross-sectoral planning that will be politically feasible and considered legitimate, accepted and owned by all key actors.

It is important to ensure that land and water are mainstreamed in national food systems pathways and country sectoral planning, including agriculture, environment and land use. FAO supports countries in developing their actions and policies including their nationally determined contributions (especially for the agriculture, livestock, fishery and forestry sectors), National Adaptation Plans, UNCCD National Action Plans, National Biodiversity Strategies and Action Plans, National Drought Management Plans, national water road maps and national food security programmes. FAO specifically promotes the national water road maps for all the SDGs (FAO, 2023a).

The partial or complete lack of coherence between sectoral public policies and interinstitutional linkages hampers the ability to address key interdependences between food, land and water resources, and the three pillars of sustainable development: environment, economy and society. Food systems face challenges arising from unintended consequences and systemic conflicts among multiple objectives. Often, subsidies and incentives aimed at achieving a specific objective result in practices that have negative impacts in other areas. For example, the development of irrigation has improved food security and nutrition in many countries, but expansion of irrigation has also contributed to the loss of wetlands and inland fisheries, excessive groundwater withdrawals and changes in surface water flows and ecosystems, as well as to increasing inequalities in access to resources.

The management of land and water resources has implications for multiple societal objectives. Agricultural productivity-led models rarely address environmental concerns and the need to promote resilient and inclusive rural transformation (Davis *et al.*, 2024). In many cases, focusing exclusively on productivity tends to favour large-scale commercial operations and neglect environmental and social considerations. Policy coherence means adopting or adjusting policy measures to achieve multiple goals, while preventing the unintended consequences of sector-focused approaches. The Organisation for Economic Co-operation and Development – a central voice on policy coherence – has extended the definition of the Policy Coherence for Sustainable Development concept beyond the fostering of synergies and trade-offs across sectors in a jurisdiction; it also reconciles domestic policy with internationally agreed objectives and considers the transboundary and long-term effects of policies in order to address trade-offs and enhance synergies.

Evidence demonstrates that restoring degraded resources, promoting sustainable intensification and increasing resilience can be achieved through joint cross-sectoral planning and implementation, greater policy coherence and multistakeholder initiatives. This can be done through territorial approaches such as watershed or river basin management, integrated landscape management and restoration, and integrated land-use planning, or through approaches such as the Water–Energy–Food–Ecosystems nexus. These approaches need to be supported by long-term strategies, investments, financing and partnerships.

Finding appropriate pathways to make these approaches work in practice is challenging (FAO, 2023b): policy coherence is not just a techno-managerial issue, but also a political one. Indeed, greater policy coherence and joint cross-sectoral planning involve taking into account the perspectives of different actors with often contradictory interests and objectives. This is further complicated by the significant rise in interconnected economic, environmental, social and geopolitical crises, all of which have had serious implications for countries' prospects for developing sustainability in line with their international commitments.

Specific barriers to policy coherence need to be recognized and identified upfront. While often of a similar nature, they differ in function of the context. Coherence challenges can arise from insufficient communication and coordination; from lack of data, funding, knowledge, shared goals or institutional spaces to meet and coordinate; and as a result of stakeholder resistance. In most cases, such challenges are driven by patterns rooted in formal and informal institutions, tenure regimes, routines or standard operating procedures in government administrations. There may be inherently contradictory interests and mandates such as conflicts between resources, conservation concerns and infrastructure development interests. Therefore, policy coherence is not only about optimization, but also about the design and facilitation of never-perfect processes of decision-making through which two or more objectives and means can be redefined, so that new (temporary) compromises can be determined.

The role of governance and political economy to support policy coherence

Governance plays a specific and crucial role in navigating interactions and collective action, especially through decision-making processes that consider potential consequences across domains and impacts on different stakeholders and actors, in particular, small-scale producers and other actors who are economically or politically vulnerable. The question of how to recognize rights and give agency and voice to those actors in decision-making processes is perhaps the most challenging and the one that deserves the most urgent attention (Nilsson, Griggs and Visbeck, 2016).

Coherence and joint cross-sectoral planning generate important benefits, but they also come with some potential downsides, from the perspective of a specific sector or agency. Such concerns include blurred lines of accountability, more time-consuming processes, uprooting of existing routines and practices, difficulties in measuring impact or effectiveness, loss of control, influence or autonomy, and dilution of priorities.

Facilitating policy coherence and joint cross-sectoral planning across food, land and water systems in a territory thus requires a good

BOX 21 REPURPOSING AGRICULTURAL SUBSIDIES

Agricultural subsidies do not always achieve the intended objectives; sometimes, the benefits do not last once the subsidies end. Therefore, it is increasingly advocated to redirect support to more sustainable and long-term investments.

Indeed, agricultural support does not provide desirable results for sustainability and human health. Repurposing it can be a game changer, offering governments an opportunity to optimize the use of scarce public resources to transform food systems, increasing efficiency and supporting the Sustainable Development Goals. Support to agricultural producers, which accounts for almost USD 540 billion a year – or 15 percent of total agricultural production value – is heavily biased towards measures that are distorting, unequally distributed and harmful to the environment and human health (FAO, 2021).

It is vital to design a repurposing strategy that considers, prior to implementation, the future impact and how to best achieve it. The strategy also requires close and gradual monitoring of the outputs and outcomes. At the same time, a review of success stories of agricultural subsidies can provide lessons to guide such repurposing. Success factors typically include capacity development and the empowerment of targeted beneficiaries in decision-making and in the financing model adopted to roll out the subsidy. It is imperative to integrate appropriate innovative financing mechanisms for the repurposing of subsidies to limit the risk of failure and guarantee a return on the investment.

Repurposing agricultural subsidies is a policy that has an impact on the scaling up of strategic finance and investments.

understanding of the local context in terms of governance and political economy. Such an understanding can be helpful in developing innovative institutional arrangements and processes to manage and coordinate policies, budgeting and regulatory development across sectors. It is also important for strengthening capacities to build on synergies, address trade-offs, and manage processes that may involve (re)allocating limited resources, addressing inequalities and changing the way of empowering actors at different levels of decision-making. Required actions include strengthening of capacity for public institutions, implementation of coordination and consultation mechanisms across ministries, adoption of appropriate planning and monitoring tools, and realization of upgraded and integrated data and information systems.

For example, improving the design of irrigation investments to include gender, health and nutrition outcomes can make irrigation an integral part of strategies to reduce poverty, hunger and malnutrition. Targeted subsidies can spur the adoption of more appropriate irrigation technology, and the provision of environmental services and measures for maintaining and restoring healthy freshwater and soil systems. Paying for environmental services – that is, payments to farmers or landowners who agree to manage their land or watersheds for environmental protection – can also help to ensure the proper valuation of well-functioning ecosystems (see Box 21).

Initiatives aimed at advancing policy coherence have emerged globally and regionally to address the challenges related to water and food security. A promising approach to coordinating water and agriculture sector policies has been adopted in the Arab region. The League of Arab States, with support from FAO and the Economic and Social Commission for Western Asia, has institutionalized coordination between the water and agriculture sectors through the establishment of a High-Level Joint Technical Committee. The joint ministerial resolution led to the 2019 Cairo Declaration,[I] which stresses the importance of enhancing policy coherence by reviewing sectoral policies on cross-cutting issues such as water allocation, non-conventional

I The Cairo Declaration was adopted during the First Joint Meeting of Arab Ministers of Agriculture and Water held by the League of Arab States in Cairo on 4 April 2019.

water resources, trade and social protection, with the goal of achieving water and food security in the Arab region.

At the International Soil and Water Forum in Bangkok, held in December 2024, representatives from 27 countries endorsed the Ministerial Declaration on managing water scarcity and reversing soil degradation for sustainable and resilient agrifood systems. The declaration recognizes the importance of "strengthening cross-sectoral coordination, cooperation mechanisms and the consistency of policies, planning, investment and implementation across land, soil, water, agriculture, climate change, biodiversity, environment, and energy" as the first urgent action to accelerate agrifood systems transformation (FAO, 2024a).

Enabler 2: Governance of natural resources

Land tenure

Land tenure security is a key enabling factor to address climate change, biodiversity loss and land degradation (IPCC, 2019, 2022; IPBES, 2018; Verburg *et al.*, 2019). UNCCD Decision 26/COP14, Decision 27/COP15 and Decision 28/COP16 repeatedly acknowledged the relevance of land tenure to achieve land degradation neutrality (UNCCD, 2019, 2022). Safeguarding legitimate tenure rights of Indigenous Peoples has also been integrated under the the Kunming-Montreal Global Biodiversity Framework (GBF) of the Convention on Biological Diversity (CBD, 2022, Target 22).

Governance of tenure and land tenure are interrelated but distinct concepts. A responsible governance of tenure relates to mechanisms and processes that articulate the interests of different actors, mediate their differences and ensure that their rights and duties with respect to land, water or other natural resources are exercised with transparency and equity. Land tenure can be defined as "the relationship, whether legally or customarily defined, among people, as individuals or groups, with respect to land", or in simpler terms: "tenure systems determine who can use what resources for how long, and under what conditions" (FAO, 2022a). Another relevant concept when discussing the importance of land tenure to achieve food security and global environmental goals is tenure security, which can be defined as "the guarantee of continued occupancy or use rights whether by virtue of formal rights, customary rules or other forms of assurance" (AGROVOC, 2022 in FAO and UNCCD, 2022). In short, it could be said that land tenure security is a result of the responsible governance of tenure of lands.

The adoption of the VGGT by the Committee on World Food Security in 2012 – and their revision in 2022 – enabled the definition of the concept of "legitimate tenure rights" (FAO, 2022a). This concept invites states to review the customary tenure rights in use and socially accepted, and to promote their recognition through the revision of their legal frameworks, offering a pathway to address the dichotomy between formal and informal tenure arrangements.

In 2022, FAO and the UNCCD Secretariat produced a technical guide supporting the integration of tenure into implementation of the UNCCD and Land Degradation Neutrality framework (FAO and UNCCD, 2022) and launched a joint initiative on tenure security for land restoration to support the integration of tenure in the achievement of LDN targets and programmes at national level.[m, n] More than 30 countries have applied to join the initiative. National consultations in a first group of countries (Kazakhstan, Kenya, Mexico, Senegal, Sri Lanka) demonstrated the relevance of gathering stakeholders from both the tenure and the land management communities (FAO and UNCCD, 2024) to advance concrete recommendations to tackle land tenure insecurity.

At national level, improving tenure security and its governance can be addressed by reviewing the policy and legal framework to sustain the recognition of legitimate tenure rights and plan for tenure security enhancements. Land or water governance raises questions of resource-related rights, risks, responsibilities, benefits and incomes, as well as of voice, power and authority.

m For more details see: https://www.prindex.net

n For more information about the FAO–UNCCD joint initiative, see: https://www.fao.org/land-water/land/tenure-ldn/fao-unccd-joint-initiative/en/#:~:text=UNCCD20and20FAO20have20launched,be20held20in20late202024

The evolution of land and water resources on the ground corresponds to the history and evolution of related institutions. In most – if not all – countries, several legal regimes related to water and land management and use have coexisted in the past and often continue to do so today.

Since the adoption of the VGGT, a series of methodologies, tools and approaches have been developed (Cotula and Knight, 2021; FAO, 2016a). They include legal assessments (Davies, 2015) and governance assessments providing practical approaches to understand the institutional contexts, asymmetry of power and bottlenecks (Batchelor *et al*., 2016; Bojić, Clark and Urban, 2022; FAO, 2024b) and governance of tenure (Deininger, Selod and Burns, 2012).

To be effective, the delivery of these reviewed policy and legal frameworks must be supported through modernized and organizational frameworks that are fit for purpose (digital cadaster, land administration), while reinforcing monitoring of its effects on the ground. A key question to ask should be: Is tenure security improving? Since most land degradation happens on agricultural land, insecure land tenure can be a major obstacle to adopting better farming practices that increase production without exhausting soil and water resources.

Water tenure

Over the past few years, FAO and partners have explored the concept of water tenure through a series of publications (FAO, 2016b), expert roundtables (FAO, 2020, 2024c) and seminars (Hodgson *et al*., eds, 2024). Monitoring the allocation of water resources is complex and costly, and water abstractions are often not quantified. This is particularly true of the irrigation sector, which in many countries accounts for the bulk of water abstracted. A further challenge is to consider all legitimate water users in water balances, including small-scale and instream uses. Nevertheless, a clear assessment of all water uses is required if water tenure is to be addressed in an effective and just manner.

FAO has developed a methodological framework to assess water tenure arrangements as part of a comprehensive water resources assessment, with a view to improving water allocation systems (Hodgson *et al*., 2024). The methodology has been tested in five countries (Indonesia, Rwanda, Senegal, Sri Lanka and Viet Nam) and is currently being applied in Cambodia, Colombia and Thailand (Al'Afghani, Lê Văn Chính and Hodgson, 2024).[o]

The water tenure assessment methodology developed by FAO allows the identification of water tenure arrangements based on formal law as well as customs and local practices in a given area, together with the legal status and perceived security of these arrangements (Hodgson *et al*., 2024). The process of water tenure assessment has been shown to empower local and marginalized water users and unmask inequalities in water access and distribution (Espinosa and Kiersch, 2024). Of particular importance are: i) the clear prioritization of water uses; and ii) the protection of small-scale users who abstract water for domestic and small-scale productive uses such as home gardening. These uses are often exempt from permit requirements or other formal tenure arrangements and, as a result, frequently lack adequate legal protection.

The reforms of legal, policy and organizational frameworks and their monitoring need to be linked to coordination mechanisms that support the meaningful and informed participation of multiple sectors and stakeholders. To achieve their effective participation, stakeholders – especially vulnerable groups – should be supported to counterbalance asymmetries of power in negotiation processes. At the local level, a nuanced understanding of formal and customary tenure arrangements improves knowledge and empowers local users of natural resources. This can be a first step to improving the tenure security of local land and water users, smallholders, pastoralists and fisherfolk, who largely depend on customary tenure arrangements to support their livelihoods. In Rwanda and Sri Lanka, water tenure assessment processes have motivated government agencies responsible for water allocation to reach out to local water users to formalize their legitimate claim to water resources (Espinosa and Kiersch, 2024).

o For more information see: https://www.fao.org/in-action/knowat/wt-assessment/country-assessments/en/ and https://www.fao.org/in-action/scalewat/en

In 2022, the FAO Committee on Agriculture reviewed FAO's work on water tenure (FAO, 2022b). It encouraged countries to participate in a Global Dialogue on Water Tenure,[p] with a view to discussing principles for responsible governance of water tenure. The aim was to strengthen the secure and equitable access to water resources of all legitimate water users, including women and marginalized groups, in support of the wider goals of health, food security, social inclusion and climate resilience (FAO, 2022c). Within this framework, a regional consultation on water tenure was held at the International Soil and Water Forum in Bangkok in December 2024.[q]

Enabler 3: Data, information and technology

The availability, quality and accessibility of data at all levels are prerequisites for the effective and sustainable management of land and water resources. Good progress has been made recently, in particular through remote sensing and communication technologies, allowing the collection of much better knowledge on water and land resources and their use, including real-time or near real-time data. Challenges remain, however, regarding the collection of specific types of data and ensuring that the right data are accessible to the right people at the right time. Integration across the data domain is still in its infancy. Different types of data are needed at different levels of management:

- **At local level**, farmers need access to real-time information on soil moisture, soil nutrient content, weather forecasts, water availability and reliability of supply, as well as early warning data on pests and pest control, to ensure good harvests. Real-time evolution of market prices is critical to ensure the best return from investments. Seasonal weather forecasts provide insights into production potential. Mapping trends associated with climate change is critical to ensure the resilience of long-term investments.
- **At national and river basin level**, developing effective and coordinated strategies requires good knowledge of the accessible resources and the trends in their use and availability, as well as monitoring of economic, social and environmental performance. More efforts must be made to invest in systematic soil, water and land-use surveys. Here, integration across sectors plays a critical role in supporting cross-sectoral coordination. Data need to be made available across ministries at minimal or no cost to their users.
- **At global level**, more and better understanding of status and trends is needed to guide global discussions and support evidence-based guidance in relation to major conventions and global initiatives. Substantial efforts are required for better monitoring of land degradation, biodiversity, progress towards sustainable agricultural practices and the impact of climate adaptation approaches.

The agroinformatics platform (previously called Hand-in-Hand Geospatial Platform)[r] gathers over 2 million data layers in support of evidence-based interventions in the field of agriculture and food security. This digital public good provides open access geographic information, key food and agriculture indicators, and agricultural statistics sourced from FAO and other organizations.

The use of digital platforms or decision support systems, based on satellite imagery, maps, drones and internet of things sensors, is gaining traction in many countries. These technologies enable farmers to optimize the use of natural resources and agricultural inputs. Mobile apps and platforms, such as FAO's AquaCrop and Water Productivity Open-access Portal (WaPOR),[s] provide real-time data on soil moisture conditions. WaPOR monitors and reports on water productivity of terrestrial vegetation in near real time, with global coverage and a 10-day time interval. Analyses of WaPOR information can also help to identify areas with potential to increase water productivity. Box 22 presents an example of a web-based decision support system for irrigation management.

p See: https://www.fao.org/in-action/scalewat/global-dialogue-on-water-tenure/en

q See: https://www.fao.org/in-action/scalewat/news/news-detail/new-water-tenure-publication-presented-during-first-regional-consultation-for-asia-pacific-in-bangkok/en

r See: https://data.apps.fao.org/?lang=en

s See: https://data.apps.fao.org/wapor/?lang=en and https://www.fao.org/in-action/remote-sensing-for-water-productivity/en

BOX 22 DECISION SUPPORT SYSTEMS FOR IRRIGATION MANAGEMENT

On-farm irrigation water management is crucial because it directly impacts the performance of irrigation schemes. Surface irrigation techniques that are widely used throughout the world often have low performance due in large part to poor water management, resulting in low water application efficiency, inequitable distribution of water across schemes, energy waste and poor soil moisture management. Improving on-farm water management, especially in water-scarce regions, is important to ensure productive and sustainable water use.

Traditional surface water management often relies on limited factual data. Methods of computation and manually collected on-farm irrigation and soil moisture data do not offer the real-time calibre of information required to support effective on-farm water management. Thanks to advances in cloud computing and the increasing availability of remotely sensed data on land surface processes and weather forecasting, it is now possible to provide on-farm water management with integrated real-time models, allowing the optimization of on-farm irrigation.

The web-based semi-automated irrigation decision support system IrrigaSys was developed to optimize water use in on-farm irrigation using open-source data and technology (Simionesei *et al.*, 2020). The system automatically accesses real-time meteorological data, weather forecasts, soil moisture dynamics and satellite-based remote sensing data. It computes weekly optimum irrigation schedules, offering a solution for efficient water use in agriculture. IrrigaSys requires minimal input from farmers (plot location, crop type, soil texture and irrigation method) and provides weekly irrigation recommendations through multiple communication platforms. The system has demonstrated significant benefits, particularly in water-scarce regions, where efficient water management is critical to increase agricultural productivity. Close collaboration with local stakeholders and continuous farmer feedback are key strengths to ensure the system's relevance and practicality. Such systems have the potential to function in a fully automated way when integrated with a Supervisory Control and Data Acquisition (SCADA) system and sensor-based irrigation monitoring.

Integration of datasets across sectors and with sustainability objectives remains a challenge. For instance, despite increasing documentation on agroecology's contributions to sustainable agriculture, there is still a critical need for harmonized evidence. The Tool for Agroecology Performance Evaluation, which is rooted in the 10 elements of agroecology (FAO, 2019), produces multidimensional evidence of the performance of agroecology across the social, ecological and economic dimensions of sustainability. It facilitates harmonized, evidence-driven decisions that can guide transformational change towards more sustainable agricultural practices (Mottet *et al.*, 2020). The use of visual narratives representing the 10 elements of agroecology can enhance food systems policy analysis by identifying intervention points, discovering co-benefit opportunities and developing integrated policy packages (FAO, 2023c).

Resilience assessment, although widely recognized as a critical development and emergency objective, remains difficult to put into practice. The Self-evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists (SHARP+) offers a comprehensive and integrated approach to analysing and measuring resilience. It is grounded in the 13 agroecosystem resilience indicators developed by Cabell and Oelofse (2012) and adopts a holistic approach to analysing and measuring an agroecosystem's resilience at the household level. The tool is designed to support evidence-based decision-making at household, project and national levels by identifying specific areas of vulnerability. It can also be used to monitor and evaluate changes in resilience over time, providing insights into the long-term impact of interventions. By targeting these weak points, SHARP+ helps to inform strategies aimed at strengthening resilience and enhancing the capacity of smallholder farmers to produce

BOX 23 USING FAO'S SEPAL PLATFORM TO ASSESS FOREST RESTORATION POTENTIAL

Effective forest restoration requires a thorough land suitability assessment to identify and prioritize suitable areas, understanding not only the ecological conditions for tree growth but also the socioeconomic impacts of restoration, including its benefits, costs and risks. FAO, in collaboration with other institutions, developed a spatially explicit online tool designed to improve strategic decision-making and plans for forest restoration as part of the System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) Open Foris platform.* The tool is capable of identifying potential trade-offs among impacts that might require further attention.

The computation is performed using cloud-based supercomputing of Amazon Web Services and geospatial datasets from Google Earth Engine, which can be accessed through SEPAL. By default, the tool utilizes global datasets such as current tree cover (Buchhorn *et al.*, 2020a, 2020b) and potential tree cover (Bastin *et al.*, 2019) as input, and provides the opportunity to integrate national data sources when available. The data layers are grouped into four categories: costs, benefits, constraints and socioeconomic conditions. Each category is scored by the user, depending on their perception of its relative importance. The area is divided into a grid, where each cell is treated as an independent unit to quantify the potential of a site to provide benefits if it is restored. The tool calculates the benefit–cost ratio by dividing the restoration value index by the estimate of the restoration cost.

NOTE: * For further details, see: https://openforis.org/solutions/sepal

sustainably in the face of climate change (Hernández Lagana, Phillips and Poisot, 2022).

Another example of the need for more integrated monitoring relates to the role of family farming in the sustainable use of forests. More robust mapping of forest foods, which estimates the nutritional and economic value that non-wood forest products provide to rural families, is needed. It should include improved valuing of the use and conservation of biological diversity and ecosystem services linked to Indigenous Peoples' knowledge. Information is also needed on the potential to strengthen value chains and markets for the responsible consumption of promising products, through which Indigenous Peoples could improve their livelihoods, while recognizing their traditional knowledge. Box 23 provides an example of a decision support system for forest restoration based on geospatial datasets from Google Earth Engine.

Enabler 4: Risk management systems including early warning and adaptation and resilience strategies

Over the past 30 years, an estimated USD 3.8 trillion in crop and livestock production have been lost due to disaster events, averaging USD 123 billion per year, or about 5 percent of annual global agricultural GDP (FAO, 2023d). As highlighted in Chapter 1, agriculture and the associated natural resources on which it depends are increasingly at risk due to a range of hazards and threats, including flooding, drought, water scarcity, declining agricultural yields and fisheries resources, biodiversity loss, sand and dust storms, and environmental degradation. Additionally, pandemics, epidemics and conflicts are disrupting agricultural production, value chains and food security, placing agrifood systems under escalating pressure.

Climate change is compounding these challenges by intensifying the frequency and severity of extreme events such as droughts, heatwaves and water scarcity. It also contributes to rising food prices and long-term risks. According to the IPCC's Sixth Assessment Report, under a high-emissions scenario (well above 1.5 °C warming), large areas currently used for crops and livestock could become unsuitable due to climate impacts – potentially affecting 10 percent of these areas by 2050 and more than 30 percent by 2100.

Understanding and addressing interconnected, systemic risks and their underlying drivers is essential for building resilient and sustainable agrifood systems that can support long-term food security and nutrition and human well-being for a growing population. Tackling these complex, overlapping challenges requires integrated, cross-sectoral solutions aligned with the objectives of the three Rio Conventions, and incorporating disaster risk reduction (DRR) strategies alongside humanitarian policies to ensure that no one is left behind.

Proactive policies, enabling incentives and increased investments in disaster prevention and preparedness yield significant returns. Farm-level DRR good practices provide, on average, 2.2 times the benefits of previous farming methods (FAO, 2019). Moreover, anticipatory action in agriculture has a return-on-investment ratio of 7:1, meaning that every USD 1 invested generates up to USD 7 in avoided losses and additional benefits (FAO, 2023c).

Natural resource management – particularly of land, water and biodiversity – plays a key role in building resilience and preventing harm from disasters and crises. Sustainable agricultural practices such as conservation agriculture, agroforestry, soil moisture management and rainwater harvesting serve both to reduce disaster risk and to enhance productivity. These are widely recognized as effective DRR good practices.

Disasters are becoming increasingly easy to predict, thanks to technological advances that have made early warning information more accurate and accessible than ever before. Expanding early warning systems for agriculture enables anticipatory action – an approach that, based on risk analysis and forecasts, triggers interventions before a crisis escalates into a humanitarian emergency, protecting livelihoods and improving resilience.

Early warning systems also support the delivery of climate services, particularly participatory climate services, which combine local knowledge with scientific data from agrometeorological systems and models, providing agricultural recommendations that help farmers to make timely decisions on crop selection, planting schedules and water use.

Finally, risk-informed planning and governance in agriculture are essential to building resilience, requiring the integration of disaster risk considerations into policies and strategies. This includes conducting risk assessments for land and water management and promoting land-use planning that reduces exposure and vulnerability as part of the ILUP processes.

Enabler 5: Sustainable financing and investment

Investing in land and water development while catering for the seemingly contradictory objectives of increasing agricultural productivity and preserving natural resources is a challenge for every government. While there has been significant growth in financing for agricultural water management, the allocation of resources remains skewed towards conventional, large-scale projects, often focusing on irrigation (Ghosh *et al*., 2022; Huber-Lee *et al*., 2021). Too often, these investments prioritize short-term productivity gains over long-term sustainability, without considering the possible degradation of natural resources, particularly land, water and soil. Recent trends, however, indicate a shift towards more sustainable and inclusive investments, driven by the growing recognition of the interdependence among water management, environmental sustainability and socioeconomic development.

To scale up investments in sustainable land management, more capital is needed. Recent estimates of the natural capital financing gap have been in the range of USD 598–824 billion per year, with current levels of funding covering only 16 to 19 percent of the overall need to halt biodiversity loss (Deutz *et al*., 2020). The transition to sustainable investments in agricultural land and water management requires coordinated efforts from governments, financial institutions and the private sector. The pathway to a sustainable future lies in fostering an enabling environment that supports integrated, inclusive and forward-looking investments in land, soil and water resources.

In many cases, the financial instruments are inadequate. There is limited availability of financial products tailored to the needs of smallholders and community-based water management initiatives, and a lack of investments in land conservation and management. Conventional financial institutions tend to favour large-scale, capital-intensive projects, leaving small-scale sustainable practices underfunded. Innovative financial instruments that adequately consider the needs of farmers in land and water development investments must be developed. Blended finance models, green bonds and impact investing are examples of instruments that can attract private investment while promoting sustainability.

Climate financing, including the new mechanism for carbon credits (the Paris Agreement Crediting Mechanism), holds potential for smallholder farmers, offering a pathway to earn revenue through carbon credits by implementing sustainable agricultural practices. These practices can generate carbon credits and bring about additional benefits such as improved soil health, increased productivity and resilience to climate change. However, challenges remain in ensuring accessibility and fairness for smallholders, including high certification costs and market volatility. Aggregation models, digital platforms and financial support can help farmers to access carbon markets and maximize their economic and environmental gains.[t]

Investments often prioritize short-term financial returns over long-term sustainability. This short-sighted approach leads to investments that may boost productivity temporarily but ultimately contribute to the degradation of land and water resources. Encouraging investors to adopt a long-term perspective is essential for the sustainability of land, soil and water resources. This can be achieved through formalizing land tenure regimes, tax incentives, subsidies and other financial mechanisms that reward sustainable practices and long-term investment strategies.

Boosting investment for biodiversity, conservation and ecosystem-based adaptation to climate change is becoming a priority. Investing in sustainable land management includes financing of businesses that contribute to biodiversity and adaptation, including sustainable forestry and agriculture, green infrastructure investments, climate mitigation projects and payment for ecosystem services (EIB, n.d.). Not only do such activities generate income for local communities, protect natural assets such as forests and water, and restore degraded lands, but the corresponding investments can also generate financial returns. Forward-looking banks, companies and other investors have in recent years made commitments to make capital available, taking into account not only financial returns, but also socially equitable and environmental returns (IDH, 2021).

It is becoming increasingly important to improve the environment for private sector investments. A promising approach to increase farmers' active participation in investing in irrigation is being promoted by the World Bank under the concept of Farmer-Led Irrigation Development (FLID),[u] which aims to improve the environment for private sector investments by empowering smallholder farmers to design and manage their irrigation systems. It fosters collaborative partnerships between farmers, government agencies and private investors, creating a more secure investment climate. By reducing risks and increasing returns through sustainable practices, FLID catalyses further investment in rural infrastructure. This innovative model builds trust, encourages technological adoption and establishes a replicable framework for scaling private sector-led rural development initiatives, driving sustainable economic growth.

Finally, investing in soft capital, including capacity building, extension services and

t The International Fund for Agricultural Development, with financial support from Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH [German Agency for International Cooperation] (GIZ), promotes one such scheme in Ethiopia through Compens Action, available at: https://compensaction.com/ethiopia

u See: https://www.worldbank.org/en/topic/water/brief/farmer-led-irrigation-development-flid digital platforms, can provide farmers with the knowledge they need to adopt sustainable practices. Public–private partnerships can play a significant role in disseminating technology and information to rural communities. Investing in rural infrastructure, including internet connectivity and affordable energy solutions, is critical to address communication barriers. Public–private partnerships can support these processes, and governments can provide incentives for technology providers to extend services to underserved areas. In addition, crowdfunding models, where farmers pool resources to share technology, can also be effective. It is also urgent to invest in early warning systems and climate information services, which provide farmers with timely and accurate data, enabling them to make informed, real-time decisions and better adapt to increasingly unpredictable and changing environmental conditions, ultimately safeguarding their livelihoods and enhancing food security.

Enabler 6: Innovation

The right environment is needed to foster innovation in sustainable land and water management. Making more productive use of irrigation water, for instance, can be achieved through increasing crop yields and reducing evapotranspiration. Significant differences in water productivity (output per unit of water consumed) across countries can be explained by farmers' access to modern agricultural inputs, efficient irrigation systems and better soil and water management.

One common mistake in seeking to increase water productivity is to focus exclusively on reducing losses at farm level, without considering implications at the level of the water system. Typically, in conventional irrigation, a substantial part of the water that is applied to crops percolates in the soil and is not used by the plant. Efforts and incentives to reduce this "loss" do not consider that the water that is not used can recharge aquifers or flow in drains and be reused further downstream. Reduction of losses at farm level therefore does not necessarily translate into more efficient use of water at the level of the basin and may lead to unintended change in water allocation across the basin.

Enhanced reliability of deliveries and greater flexibility in the timing and amount of irrigation water are important factors in farmers' investment decisions. When the supply of water is unpredictable, farmers tend to cultivate crops that are resilient to water stress and variable irrigation timing. Typically, these crops have low yields and low monetary value.

Modernization of irrigation systems can contribute to greater irrigation efficiency amid rising water scarcity, as well as to more reliable and cost-effective services that match farmers' needs and ensure increased productivity to meet growing demand. In more demand-driven, service-oriented irrigation systems, innovative tools can help farmers by indicating the optimum time and volume for irrigation. Such tools can use real-time information on evapotranspiration and soil moisture to optimize on-farm irrigation practices. Innovation, therefore, lies as much in changes in managerial capacities as in technological upgrades – sometimes even more.

There are several key innovations that enhance sustainable land management, particularly in the areas of technology, land-use practices, governance, and finance. Technological advances such as precision agriculture make use of Global Positioning System (GPS), sensors and data analytics to optimize inputs and boost productivity, while remote sensing supports land condition monitoring. Sustainable farming methods – like agroforestry, conservation agriculture, and integrated soil fertility management – help maintain soil health and productivity. On sloped land, terracing and contour farming are effective in reducing erosion. Governance innovations include secure land tenure, which encourages long-term investment, and community-based land-use planning, which promotes local stewardship. Financial tools such as climate-smart subsidies support land restoration and sustainable practices. At a broader level, integrated land-use planning and landscape management align efforts across sectors, while the Land Degradation Neutrality framework aims to offset degradation through restoration, ensuring no net loss of productive land.

BOX 24 THE FARMER FIELD SCHOOL APPROACH

The Farmer Field School (FFS) concept was first launched in the late 1980s by FAO in Indonesia and now operates in more than 90 countries, equipping hundreds of thousands of farmers, pastoralists and fisherfolk with the knowledge not just to boost productivity, but also to sustain the ecosystems that support their livelihoods. Recognizing the long-term threats posed by unsustainable farming practices, the FFS approach now emphasizes holistic agroecosystem management, offering farmers training on all aspects from improving soil health and managing water to regenerating degraded landscapes and tackling climate change.

Enabler 7: Institutionalized capacity development

Modern extension approaches aim to equip farmers, communities and technicians with the tools and skills needed to enhance income and food security while promoting environmental sustainability. The integration of participatory approaches, digital tools and innovative agricultural techniques, while recognizing the critical value of local knowledge, forms the backbone of modern efforts to address the complex challenges of sustainable resource management.

Understanding and approaching capacity development in its comprehensive dimension requires the use of integrated and multilevel approaches and the development of technical as well as functional skills. One valuable approach is knowledge sharing, where farmers team up and learn from each other through hands-on experiences, discussions and practical demonstrations. Another important integrated approach involves participatory training initiatives such as watershed management and integrated land-use planning, which engage communities in sustainable natural resource management.

FAO has developed two key peer-to-peer training programmes of relevance to land and water management: Farmer Field Schools (FFS, see Box 24) and the Global Soil Doctors Programme. The Farmer Field School approach not only builds the technical capacity of farmers, it makes a significant contribution to community development, including social dynamics, gender equality and social inclusion. A key to the success of FFS in tackling these challenges is a participatory learning model. Rather than delivering top-down solutions, the FFS approach empowers farmers to experiment, observe and learn by doing, helping them to understand vital processes such as soil–plant–water interactions, biodiversity and nutrient cycling. The strength of the FFS model lies in its collaborative nature. For example, in the Kagera River Basin, which is shared by Burundi, Rwanda, Uganda and the United Republic of Tanzania, FFS groups have restored degraded lands, improved biodiversity and conserved water across entire watersheds (FAO, 2017b). In Andhra Pradesh, India, the FFS approach has supported the Community Managed Natural Farming initiative,[v] showcasing its potential to regenerate ecosystems and improve livelihoods simultaneously.

To effectively address land, soil and water challenges, the FFS approach has adapted its methods to an integrated, landscape-wide perspective, encouraging farmers to view their farms as part of a broader ecosystem, learning to build organic matter, enhance soil structure and improve water retention. These practices help farmers to boost carbon sequestration and mitigate droughts, all crucial for building climate resilience. By empowering farmers to manage their natural resources wisely, FFS build resilient farming systems capable of withstanding environmental pressures, while safeguarding the planet's long-term health.

Since 2020, FAO has also implemented the Global Soil Doctors Programme to solve issues such as improper use of organic and mineral fertilizers and pesticides, and limited knowledge of soil conditions, and to promote sustainable soil management.[w] Among the programme's strengths are its high adaptability to local conditions and

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v For more information, see: https://apcnf.in

w For more information, see: https://www.fao.org/global-soil-partnership/soil-doctors-programme/about-the-programme/en

BOX 25 PRIORITIZING INSTITUTIONAL CAPACITY DEVELOPMENT

Investments in capacity development should focus on institutions rather than individuals. Institutions catering for the needs of farmers and extension officers can provide a supporting framework that optimizes the benefits. Ideally, locations should be within the proximity of the target groups; this is the case of Farmer Field Schools and extension centres, where the school or extension centre is the place of reference for training.

Institutional custodianship can also be fostered through the training of trainers model or through arrangements where the focus is on both the individual trainee and the home, resulting in sustainable learning outcomes. In the long term, institutional capacity development will produce a critical mass of trainees who gradually become experts with the latest knowledge and technologies and who adopt best practices to do business.

capacity to collaborate with national stakeholders including academia, governments, the private sector and farming communities. The programme provides efficient solutions to soil management challenges and creates a self-sustaining system at national level. To date, over 15 000 farmers in 28 countries have been trained with educational materials translated into more than 20 local languages. The programme has several success stories of local champion farmers, known as soil doctors, who train other farmers in methods for overcoming soil threats. A case in point is in Xochimilco, Mexico, where farmers are learning to manage soil salinity using compost and water filters and to monitor it through soil pH measurement. In Togo, farmers are being shown how to monitor the negative effects of burning forests on soils, through visual soil assessment of soil organic matter, root development and water retention.

FAO peer-to-peer training programmes use communication strategies and tools to promote social change, development and the adoption of sustainable practices within communities. Communication for Development (ComDev) is instrumental in combining participatory processes with the use of adequate media and digital solutions that can be adopted by family farmers, rural communities and institutions. ComDev uses a variety of communication channels such as radio, mobile phones, social media, community meetings and participatory video to reach a wider audience, including those in remote or underserved areas. This multichannel strategy ensures that farmers with various levels of access to technology can benefit from the information provided. It also ensures that solutions are locally relevant and that farmers feel ownership of the changes being promoted.

In addition, the ComDev approach enables the co-creation of knowledge by encouraging farmers to share their own experiences, as well as traditional or Indigenous Peoples' knowledge, which can be integrated into the training modules. In Zambia, global research partnership CGIAR has been supporting reality TV shows created by national broadcasters to teach climate-smart agriculture and provide climate information services to millions of farmers on a weekly basis (CGIAR, n.d.). Strengthening extension services through participatory capacity development, increasing the number of trained extension agents and integrating local languages into training materials are all essential. Given the success achieved by peer-to-peer learning models, these should be further promoted by broadening the approaches and thematic areas covered, reinforcing principles of inclusivity and gender responsiveness, and respecting local traditions, while promoting the knowledge and use of digital technologies. Adapting such approaches to targeted interventions can significantly accelerate the adoption of sustainable land, soil and water management practices, which will ultimately support long-term agricultural sustainability and resilience (see Box 25). ■

LOOKING AHEAD: OPPORTUNITIES FOR CREATING AN EFFECTIVE ENABLING ENVIRONMENT

The urgency of scaling up solutions to the interconnected climate, land and water crises is recognized in many international processes, such as the United Nations Convention to Combat

Desertification, the Kunming-Montreal Global Biodiversity Framework of the Convention on Biological Diversity, the UN 2023 Water Conference, the SDG Summit 2023, and the Global Framework on Water Scarcity in Agriculture (WASAG). It is also a priority within FAO, as reflected by the adoption of the FAO Conceptual Framework for Integrated Land and Water Resources Management (FAO, 2025b). The framework expresses the Organization's vision for integrated land and water resources management, as well as its mission, five outcomes, the means for their achievement and linkages to the Programme Priority Areas of the FAO Strategic Framework 2022–2031 (see Figure 28).

The **United Nations Convention to Combat Desertification** highlights that climate change, land degradation and water scarcity are deeply interconnected and cannot be addressed in isolation. Land degradation exacerbates climate impacts and water shortages, while climate change accelerates desertification and disrupts water cycles (Orr *et al.*, 2017). The convention stresses the importance of creating an enabling environment for land degradation neutrality that enhances the well-being of land users and those whose livelihood depends on land (Verburg *et al.*, 2019). In 2024, the sixteenth session of the Conference of the Parties (COP) of the UNCCD, held in Riyadh, adopted Decision 19/COP16 on "avoiding, reducing and reversing land and soil degradation of agricultural lands".[x] The decision calls for promoting sustainable land use to prevent and reverse the degradation of agricultural lands and soils in the context of climate change and environmental degradation. This is expected to influence future discussions and enhance the engagement of agriculture ministries and farmers.

The **Kunming-Montreal Global Biodiversity Framework**, adopted in 2022, set targets through to 2030 for the protection of nature, including for land, soil and water resources, as well as agroecosystems. It identifies land-use change as the major direct driver of biodiversity loss, having had the largest negative impact on terrestrial ecosystems since 1970, with agricultural expansion being the most widespread form of land-use change. Target 1 aims to bring the loss of areas of high biodiversity importance close to zero by 2030 through participatory, integrated and biodiversity-inclusive spatial planning. Target 2 aims to ensure that by 2030 at least 30 percent of degraded areas are under effective restoration; this target links to the **UN Decade of Ecosystem Restoration 2021–2030**. Countries are encouraged to mainstream effective ecosystem restoration into their policies and plans and to build upon and reinforce existing restoration initiatives in order to scale up good practices. Regional restoration initiatives include the Pan-African Action Agenda on Ecosystem Restoration for Increased Resilience (CBD, 2018).

FIGURE 28 FAO CONCEPTUAL FRAMEWORK FOR INTEGRATED LAND AND WATER RESOURCES MANAGEMENT

VISION

- Land, soil and water resources conserved, restored and sustainably used to ensure future food and water security and ecosystem services

MISSION

- Provide policy guidance and technical assistance to Member Nations and support strategic interventions and innovations on efficient and sustainable use of land, soil and water resources

OUTCOMES

- Good governance of land, soil and water resources
- Conservation, restoration and sustainable use of land, soil and water resources
- Increased adaptation and resilience to climate change and reduced greenhouse gas emissions
- Integrated land, soil and water solutions
- Optimized land, soil and water data and information systems for agrifood system transformation

MEANS

- Mobilizing resources and partnerships
- Network-wide joint programmes/projects
- Effective teams (Land and Water Division and network)
- Knowledge management (sharing and learning)
- Outreaching and communications

PPAs

- Programme Priority Areas

SOURCE: Adapted from FAO. 2025. *FAO Conceptual Framework for Integrated Land and Water Resources Management.* Rome. https://openknowledge.fao.org/handle/20.500.14283/cd4847en

x See: https://www.unccd.int/sites/default/files/2025-03/19-cop16.pdf

Effective restoration activities include reducing unsustainable resource use, rehabilitating ecosystem functions and services – for example, through agroecological practices and nature-based solutions – and reducing or removing contaminants and pollutants, including pesticides and herbicides (FAO *et al*., 2021). Restoration thus links to Target 11 of the Global Biodiversity Framework, which calls upon countries to "restore, maintain and enhance nature's contributions to people, including ecosystem functions and services, such as regulation of air, water, and climate, soil health, pollination and reduction of disease risk, as well as protection from natural hazards and disasters, through nature-based solutions and/or ecosystem-based approaches for the benefit of all people and nature".[y] This new emphasis on the implementation of ecosystem-based approaches is an important opportunity to innovate and create development that supports the well-being and resilience of people and of nature.

The **UN 2023 Water Conference** (United Nations, 2023a), held in New York, United States of America, acknowledged that the global water cycle is out of balance. The Global Commission on the Economics of Water,[z] convened in the lead up to the conference, underscored the importance of governing water as a global common good, recognizing the deepening interconnections between the water crisis, climate change and the loss of the Earth's natural capital, as well as how water flows through all 17 Sustainable Development Goals (Mazzucato *et al*., 2024). The conference called for overcoming the dependency of food and power on water consumption, emphasizing the need for climate-smart food sources to contribute to sustainability and the adaptation of agriculture, enhancing supply chain efficiency and empowering small communities. It noted the benefits of improving agricultural water-use efficiency and addressing sources of water pollution as important opportunities for more sustainable water management in agriculture and reduced pressure on ecosystems and societies. While the conference outcome document is not legally binding on countries, the conference has been key to improving global-, regional- and national-level water governance.

The **2023 SDG Summit**, also held in New York, United States of America, reaffirmed the commitment of countries and the United Nations system to accelerate implementation of the 2030 Agenda for Sustainable Development. Regarding SDG 2 (Zero Hunger), the conference committed to accelerating actions to end hunger and food insecurity, including by promoting sustainable and resilient agriculture and food systems. For SDG 6 (Clean Water and Sanitation), the conference committed to addressing water scarcity and to driving transformation from a global water crisis to a world where water is a sustainable resource (United Nations, 2023b).

An important global mechanism to help drive this transformation is the **Global Framework on Water Scarcity in Agriculture (WASAG)**, a partnership hosted by FAO. WASAG partners, including national governments, noted that changing rainfall patterns – including the resulting droughts and floods – increasing water pollution, deteriorating water quality and a warming climate put at risk the food security, water security and livelihoods of farmers and people worldwide.[aa] The partners committed to improving water governance to address the effects of water scarcity and climate change on global food security, to create sustainable, resilient and inclusive agrifood systems, and to position agriculture at the core of international climate change discussions. One key action area is to strengthen collaboration at national level on addressing water scarcity in agriculture. Ministries of agriculture need to work together with water, environment and other ministries connected to water resources to cooperate on policy approaches, legal and institutional frameworks, investments, data, information and knowledge-sharing. This collaboration includes regional initiatives such as regional water scarcity programmes and the **inter-Regional Technical Platform on Water Scarcity**.[ab] ■

y For more information on Target 11 of the GBF, see: https://www.cbd.int/gbf/targets/11

z See: https://www.watercommission.org

aa For more information, see: https://www.fao.org/wasag/news/outcomesofthehigh-levelromewaterdialogueonwasag/en

ab For more information, see: https://www.fao.org/platforms/water-scarcity/en

CHINA
A farmer works on the Longji Rice Terraces in Guangxi.
© Guang Sheng

CHAPTER 6
CONCLUSIONS

THE CHALLENGES

Land, soil and water form the foundations of agricultural production. In order to meet the demands of a growing global population, FAO estimates that by 2050, agriculture needs to produce about 50 percent more food, feed and fibre than it generated in 2012. Achieving this objective will place additional pressure on the world's already overstretched water, land and soil resources.

Land productivity has increased substantially in response to increasing demand, but this has often had a negative effect on the environment.

Human-induced land degradation affects agricultural lands and the people depending on land for their livelihoods.

Unprecedented pressure on land, soil and water resources, with competition between sectors, is increasingly affecting agriculture, as productive land is lost and water availability reduced.

Social and gender inequalities persist in access to and governance of land and water resources; this undermines food security, especially for the most vulnerable groups.

Climate change affects all components of agrifood systems, including land, soil and water resources. Sustainable management of these vital resources can play a key role in both mitigation of and adaptation to climate change. However, investments and climate finance continue to be scarce and inadequate.

Climate mitigation and adaptation measures need to be carefully planned to avoid maladaptation or unintended consequences, including additional pressure on scarce water resources or further degradation of land resources. ■

STATUS AND TRENDS

Agriculture is the economic sector with by far the greatest impact on land and water resources.

More than 1 660 Mha of land, corresponding to more than 10 percent of the world's land area, have been degraded by unsustainable land-use and management practices (human-induced land degradation); more than 60 percent of this degradation occurs on agricultural lands (including cropland and pastureland).

Over the 60-year period between 1964 and 2023, most of the increase in agricultural production was due to intensification – for example, through adoption of improved seeds and agronomic practices, better access to water and more systematic use of fertilizers – while the expansion of agricultural land was limited to just 8 percent.

From 2001 to 2023, total agricultural land area decreased marginally: cropland increased by approximately 78 Mha (a 5 percent increase), while the area for pastures declined by 151 Mha (a 4 percent decrease).

Permanent crops, including oil palm, coffee, tea and other tree crops, increased by 42 percent between 2001 and 2023.

Irrigated land is 3.2 times more productive than rainfed land. In 2022, 22.5 percent of all croplands were irrigated and produced 48 percent of the total economic value of agricultural production. On average, irrigated land yields 76 percent more than rainfed land.

Intensification has made it possible to limit further expansion of agricultural land (in places, even reducing agricultural land) and encroachment on other lands.

Increase in agricultural production, whether through expansion or intensification, has come at a high environmental cost, contributing to a substantial share of GHG emissions and biodiversity loss, degrading land and inland water ecosystems, polluting soils and aquifers, and pushing water withdrawal beyond sustainability limits in an increasing number of regions.

About one-sixth of the global population (i.e. 1.2 billion people) live in agricultural areas (both rural and urban) with severe water constraints. Some 72 percent of global freshwater withdrawals are for agriculture.

Further efforts are required to achieve more efficient use of water, and ensure that water withdrawal, whether from surface water or groundwater, takes place within the sustainability limits.

Future agricultural development pathways need to be based on the transformation of agrifoods systems for better production, better nutrition, a better environment and a better life, leaving no one behind. The additional production required to satisfy the future increase in demand must be realized through more efficient, inclusive, resilient and sustainable production systems that address the socioeconomic and environmental dimensions of sustainable development. It is essential to consider risks such as those related to human-made or natural disasters, epidemics and conflicts. ■

THE POTENTIAL TO PRODUCE MORE AND BETTER

The potential exists to feed the 9.7 billion people predicted to make up the world's population by 2050 and the approximately 10.3 billion people when the world population is projected to peak around 2085. The conditions in which this production takes place will determine the associated environmental, social and economic costs.

Globally, the land suitable for cultivation is substantial, totalling more than 4 billion ha. However, the potential for agricultural expansion is limited, as further land conversion to cropland would impact other ecosystems, including forests, grasslands and wetlands.

The assessment of land suitability for cultivation in this report is based only on the characteristics of the land; it does not consider existing land use and whether any conversion to cropland is acceptable. For instance, expansion of agriculture into existing forests is not a strategic option, even when the land offers high levels of suitability for cultivation.

The report provides alternative areas for sustainable expansion to enhance food production and, at the same time, safeguard forestlands and protected areas, thereby responding to sustainable land-use commitments under the Rio Conventions (CBD, UNCCD, UNFCCC) and the Sustainable Development Goals.

Land suitable for crop cultivation is not distributed evenly across the world, with regions such as Africa and South America showing opportunities for further expansion, while other regions such as the Near East have mostly reached their limits and, in some cases, are experiencing a reduction in area under agriculture.

Climate change affects land suitability for many crops, with suitable areas for given crops tending to move to higher latitudes and altitudes. For some crops, agricultural water demand will increase in future climate scenarios, while the available water resources will become more variable and less reliable. Climate change is expected to cause an increase in extreme events such as droughts. For agriculture to adapt to more frequent droughts, it is expected that areas normally under rainfed agriculture will be increasingly equipped for irrigation. As soon as such areas are equipped, it is likely that supplementary irrigation will be used to increase cropping intensities and yields.

Most agricultural production is practised on prime or good agricultural land. However, there are areas where population pressure and limited resources force farmers to practise agriculture on marginal land.

Efforts to meet future demand for food must above all involve a more efficient, sustainable and productive use of existing agricultural land (sustainable intensification is key). It is critical to ensure that intensification is pursued in a far more sustainable manner than it was in the past. For intensification including water management techniques, water accounting is key in order to assess the consequences for water availability for environmental flows in river basins and aquifers.

There is scope for significant increases in land productivity in most developing regions and for most types of crops. This increase can come mainly from a reduction in yield gap through the selection of suitable crops and the adoption of sustainable management practices for each crop.

There is also substantial scope for increases in water productivity, but much less for increases in water use, especially in arid areas. Water productivity can be increased by adopting improved crop farming practices and water management techniques such as water harvesting measures and demand-based irrigation.

It is possible to enhance the productivity of marginal land through suitable land use, adopting practices to address the limiting production factors and promoting appropriate enabling environments. ■

TECHNICAL SOLUTIONS TO ACHIEVE BETTER PRODUCTION

Multiple technological solutions exist to achieve sustainable land, soil and water management. They depend on the socioecological context and production systems, which determine the appropriate enabling environment.

The productivity of rainfed agriculture can be improved through the adoption of conservation agriculture, use of drought-tolerant crop varieties, implementation of drought-resilient practices (e.g. soil moisture conservation, crop diversification and organic composting) and application of diversified and adapted production systems (e.g. agroforestry, including agrosilvopastoral systems).

The productivity of water in irrigation can be enhanced through a combination of water management and agronomic practices. Modernization of irrigation is key to reducing yield gaps and increasing water and land productivity.

Better land and water management for pasture and feed production can be achieved by improving water management and grazing practices, selecting drought-tolerant and water-efficient species, integrating alternative forage and legumes in pastures, and adopting precision livestock farming technologies.

The importance of urban and peri-urban agriculture as a component of the world's food production systems is growing. Hydroponics, and vertical and rooftop farming are proven techniques used to increase the efficiency of UPA and reduce competition for land, water, energy and labour.

Forests sustain the livelihoods of millions and contribute to global objectives such as climate change mitigation and adaptation and biodiversity conservation.

Restoring degraded lands, promoting agroforestry and building green value chains for forest products – including non-wood forest products and agricultural products from opportunity and traditional crops adapted to local environments and cultures – are critical for maintaining and tapping the potential of forests and trees and local rich agrobiodiversity for sustainable agrifood systems.

Inland fisheries offer significant potential for increased fish production and require an integrated approach to water management. Fast-growing inland aquaculture offers opportunities for integrated food production (e.g. rice–fish farming systems).

Irrigation and water harvesting techniques can manage soil moisture and ensure an adequate water supply to crops, which enhances the potential of land for increased crop production.

The availability and the quality of soil nutrients are among the main constraints limiting production in many areas. This issue can be addressed by introducing better agricultural practices, including improved nutrient-use efficiency, promotion of balanced fertilization with integration of organic inputs, sustainable use of fertilizers, mechanization, adoption of improved crop varieties, and promotion of agrobiodiversity, including the cultivation of opportunity crops adapted to specific conditions and cultures.

In degraded agricultural lands, there is scope to increase production and productivity through land and soil restoration, using sustainable land and soil management practices, while also addressing the root causes of land degradation.

Integrating sectoral solutions offers a unified model for sustainable land, water, forest and aquatic resource management that addresses multiple aspects of food security, climate resilience and environmental sustainability. Examples of such integrated approaches are agroforestry, rotational grazing and forage improvement, and rice–fish farming. Together, these technologies and practices create a framework where sustainable resource use is tailored to specific landscapes in order to enhance climate change resilience. ■

AN ENABLING ENVIRONMENT TO SUPPORT TECHNICAL SOLUTIONS

Sustainable and integrated solutions are required to address the intricately linked food, climate, land, soil, water and biodiversity crises.

These solutions comprise integrated land-use planning, integrated landscape management, integrated water resources management, the Water–Energy–Food–Ecosystems nexus approach, agroecology and the agrifood systems approach.

Adopting the WEFE nexus approach acknowledges the interconnectedness between these components and their impact on ecosystems. It allows to maximize synergies, reduce risks, and support practical actions in collaboration with stakeholders.

In order for such integrated land, soil and water resource management solutions to be implemented coherently at scale, the following enablers will need to be set in place: policy coherence across sectors; governance of natural resources; data, information and technology; risk management systems including early warning and adaptation and resilience strategies; sustainable financing and investment; and innovation and institutional capacities.

Better coherence between sectoral policies is needed to maximize the gains associated with land and water management and to address overlaps and trade-offs between conflicting objectives. This requires adapting and strengthening of institutions and regulatory environments.

Stronger policies to promote sustainable land, soil and water management should include clear land and water rights, in addition to incentives for sustainable practices and disincentives for unsustainable ones. Regulatory frameworks can create a more conducive environment for public and private sector investments.

Securing access to resources for smallholders and vulnerable groups offers the potential to enhance productivity, protect resources and contribute to inclusive rural development.

Data and information are key to ensuring the sustainable and productive management of land and water. The rapid development of information and communication technologies, including remote sensing, offers new opportunities for support to land and water management. Efforts should be made to ensure that the right information reaches decision-makers at all levels.

Public and private investment instruments that increase agricultural productivity, contribute to inclusive development and preserve natural resources need to be developed and put into practice. Sustainable investments require coordinated collaboration between the public sector and the financial and private sectors.

Farmers, especially in developing regions, often lack access to the necessary technologies, information and skills required to implement sustainable practices; this hinders the adoption of innovative and sustainable land and water management techniques. Farmer-centred training programmes should use modern communication technologies to promote the adoption of sustainable practices that strengthen resilience while ensuring the overall improvement of farmers' socioeconomic status.

In areas where land and water resources are scarce, satisfying competing societal objectives (agriculture, industry, urban development, energy, biodiversity conservation) often implies trade-offs and difficult choices in resource allocation. Integrated land and water resource planning provides tools to manage the competition for resources and optimize their use.

The need for integrated solutions to the food, climate, land, soil, water and biodiversity crises is emerging from recent international processes, their various calls for action and the setting of targets and commitments that aim to accelerate the achievement of the Sustainable Development Goals. These integrated solutions offer a framework for countries to enhance their efforts towards addressing these intertwined objectives in an integrated manner.

Integrated land-use planning is needed at different levels of decision-making to address emerging challenges and increased competing demands.

An evidence-based integrated planning process – supported by suitable tools and practices, and incorporating different sectors and stakeholders, as well as emerging opportunities and challenges – is essential. FAO's forthcoming nine-step guidelines for integrated land-use planning aim to facilitate this process.

Field programmes should be designed and implemented to utilize the updated integrated land-use planning and integrated landscape management tools and to fine-tune them to support land-use decisions at different levels while ensuring inclusivity and responsible governance.

An integrated water resources management approach is recommended to optimize the allocation of water across various uses, including different crop types, fisheries, aquaculture, livestock, and non-agricultural sectors such as domestic supply, energy, industry and recreation. ■

ANNEX

1. THE GLOBAL AGRO-ECOLOGICAL ZONING METHODOLOGY (GAEZ)

1.1 Assessing land suitability for different crops

The Global Agro-Ecological Zoning (GAEZ) database represents the main source of information for the analysis of land suitability and yield gaps in this report, and for the assessment of climate impact on land suitability.

The GAEZ methodology, developed by FAO and IIASA, models the crop cultivation potential as the attainable limit to produce individual crops under given agroclimatic, soil and terrain conditions for specific levels of agricultural inputs and management (Fischer *et al*., 2021).

The levels of inputs and management are a central element of the GAEZ methodology. There are two main levels: high input and low input (Fischer *et al*., 2021).

- **Low-level input/limited management.** Under the limited management assumption, the farming system is largely subsistence-based and not necessarily market-oriented. Production is based mainly on the use of local cultivars, labour-intensive techniques. It entails no application of fertilizers, no use of chemicals for pest and disease control and minimum conservation measures.
- **High-level input/advanced management.** Under the advanced management assumption, the farming system is mainly market-oriented; producing producing for the market is a management objective. Production is based on improved varieties and mechanization with low labour intensity. It uses optimum applications of nutrients and chemical pest, disease and weed control.

The management level influences land suitability for a given crop. High-level management can alleviate some of the constraints that low-level management cannot address. Therefore, the extent of land suitable for a given crop under advanced management is usually greater than under limited management. GAEZ also considers two other categories not used in this report: intermediate-level and mixed-level management conditions.

The GAEZ modelling framework uses established land evaluation principles (FAO, 1976) to assess natural resources and determine suitable agricultural land-use options. It examines resource limitations and opportunities by considering the ecophysiological, climatic and soil requirements of different crops. These factors are used to evaluate the suitability and production potential of individual crops under various management conditions (Fischer *et al*., 2021). Comparing production potential with production statistics allows to calculate yield gaps and identify hotspots for more productive land use.

Georeferenced global climate, soil and terrain data are combined into a land resources database, which is assembled based on global grids, at 5 arc-minute and 30 arc-second resolutions. The land resources are matched with the crop-specific requirements and limitations regarding climate, soil and terrain properties under assumed levels of inputs and different management conditions (low- and high-input management levels).

Climatic data comprise precipitation, temperature, wind speed, sunshine duration and relative humidity. For soil, the agroecological zoning identifies seven soil qualities; these are combined into a crop- and input-specific edaphic suitability rating, which is integrated with information on prevailing terrain-slope conditions.

The GAEZ models provide attainable crop yields for each basic land resources unit under different land utilization types (LUTs). LUTs are generic agricultural production systems defined by crop parameters (e.g. harvest index, maximum rate of photosynthesis, maximum leaf area index), water supply systems (rainfed, irrigated) and levels of inputs and management (ranging from low to high). In this study, land suitability was analysed for four crop groups: cereals; pulses; oil crops; and roots and tubers.

1.2 Methodology to compute yield gaps

The computation of yield gaps in **Chapter 3** was done as follows:

- **Step 1.** Download summary crop tables[ac] from the GAEZ v5 database for each crop in the selected crop group (cereals; pulses; oil crops; and roots and tubers), by source of water (rainfed/irrigated) and with high-input management level, selecting the area under current cropland.
- **Step 2.** Compute an average yield by cropland rainfed and cropland irrigated separately, based on the extent of the classes of suitability (i.e. very suitable; suitable; moderately suitable; marginally suitable; very marginally suitable).
- **Step 3.** Compute average yield values from the cropland rainfed and the cropland irrigated simulations respectively, by country and crop type.
- **Step 4.** Download FAOSTAT data on area harvested, productions and yields, by country and crop for the period 2001–2020 (FAO, 2025). Compute average values by country and crop over this period, accounting for eventual administrative changes during this period.
- **Step 5.** Compute an adjusted attainable yield to convert GAEZ v5 values to fresh matter as in FAOSTAT statistics (Equation 1).

Equation 1:

$$Attainable\_yield_{adj} = GAEZ5\ Attainable\_yield * 1/ConvFactor$$

where:
$Attainable\_yield_{adj}$ is the adjusted yield (kg/ha), estimated by crop and country;
GAEZ5 Attainable_yield is the GAEZ v5 yield, estimated by crop and country; and
ConvFactor is the conversion factors (dimensionless), by crop, used to transform GAEZ v5 values (in dry matter) to fresh matter as in FAOSTAT.

The conversion factors for each crop in the four crop groups are derived from Table 9-1, p. 142 of the GAEZ model documentation (Fischer *et al.*, 2021).

- **Step 6.** Compute differences between attainable and actual yields (in kg/ha).
- **Step 7.** Compute the yield achievement ratio as the ratio between actual and adjusted attainable yield (in percentage).
- **Step 8.** Compute the yield gaps as the difference between 1 and the yield achievement ratio (in percentage).

It should be noted that this methodology differs from the yield achievement ratio product, which is computed by GAEZ at pixel level and, at the time of writing, was not yet available for version 5.

1.3 Methodology to assess the impact of climate change on land suitability

The GAEZ v5 update, used here, includes the most recent global data on land cover and land use, soil, elevation, protected areas, and climatic conditions for the historical period 1981–2020. It uses AgERA5-derived products provided by the Copernicus programme (C3S, 2023), together with a selection of climate simulations using up-to-date models from the Coupled Model Intercomparison Project 6[ad] in IPCC (2023) for three SSPs. Shared Socioeconomic Pathways are a set of scenarios used to describe possible future socioeconomic developments. They are designed to explore how global society, demographics and

ac GAEZ v5 Crop summary data are available for download at: https://data.apps.fao.org/gaez/?lang=en

ad The Sixth Phase of Coupled Model Intercomparison Project (CMIP6) is an updated version of Phase 5 (CMIP5) with similar radiative forcing levels for 2100. CMIP6 involves coordinated efforts from around 100 distinct climate models produced by 53 modelling groups.

TABLE A.1 SHARED SOCIOECONOMIC PATHWAYS IN THE IPCC SIXTH ASSESSMENT REPORT

SSP	Scenario	Warming (best estimate) (2041–2060)	Warming (best estimate) (2081–2100)	Very likely range (2081–2100)
SSP1-1.9	Very low GHG emissions: CO_2 emissions cut to net zero around 2050	1.6 °C	1.4 °C	1.0–1.8 °C
SSP1-2.6	Low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7 °C	1.8 °C	1.3–2.4 °C
SSP2-4.5	Intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0 °C	2.7 °C	2.1–3.5 °C
SSP3-7.0	High GHG emissions: CO_2 emissions doubled by 2100	2.1 °C	3.6 °C	2.8–4.6 °C
SSP5-8.5	Very high GHG emissions: CO_2 emissions tripled by 2075	2.4 °C	4.4 °C	3.3–5.7 °C

NOTE: GHG = greenhouse gas; CO_2 = carbon dioxide.

SOURCE: IPCC. 2023. Sections. In: H. Lee & J. Romero, eds. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

economics might evolve over the twenty-first century, affecting greenhouse gas emissions and climate change (IPCC, 2023). The IPCC Sixth Assessment Report assesses the climate response to five illustrative scenarios covering the range of possible future development of human-induced climate change from the literature. These scenarios are labelled according to their expected radiative forcing values by 2100 (e.g. RCP2.6, RCP4.5, RCP7 and RCP8.5) and correspond to different levels of greenhouse gas emissions and global warming outcomes.

Climate change is expected to increasingly impact land suitability. Using the most advanced tools available, such as general circulation models, it is now possible to compare current land suitability under baseline climate conditions (averaged from the period 2001–2020) with those under different climate scenarios. In this report, GAEZ v5 estimates of suitable land for four selected crops during the historical period 2001–2020 were compared with projected land suitability derived from an ensemble of five climate change models. The results are elaborated in **Chapter 3**.

More information on GAEZ v5 data and methodology, including on simulations under different climate scenarios, is available at: https://www.fao.org/gaez/en.

2. REGIONAL AGGREGATIONS

TABLE A.2 COUNTRY COMPOSITION OF THE REGIONS AND SUBREGIONS IN THE REPORT

Region	Subregion	Countries and territories
AFRICA		
	Northern Africa	Algeria, Egypt, Libya, Morocco, Sudan, [Sudan (former)], Tunisia, Western Sahara
	Eastern Africa	Burundi, Chagos Archipelago, Comoros, Djibouti, Eritrea, Ethiopia, [Ethiopia PDR], French Southern Territories, Kenya, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Réunion, Rwanda, Seychelles, Somalia, South Sudan, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
	Middle Africa	Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe
	Southern Africa	Botswana, Eswatini, Lesotho, Namibia, South Africa
	Western Africa	Ascension, Saint Helena and Tristan da Cunha, Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo
AMERICAS		
	Caribbean	Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Bonaire, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Cuba, Curaçao, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, [Netherlands Antilles (former)], Puerto Rico, Saint Barthélemy, Saint Kitts and Nevis, Saint Lucia, Saint Martin (French part), Saint Vincent and the Grenadines, Sint Maarten (Dutch part), Trinidad and Tobago, Turks and Caicos Islands, United States Virgin Islands
	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
	South America	Argentina, Bolivia (Plurinational State of), Bouvet Island, Brazil, Chile, Colombia, Ecuador, Falkland Islands (Malvinas), French Guiana, Guyana, Paraguay, Peru, South Georgia and the South Sandwich Islands, Suriname, Uruguay, Venezuela (Bolivarian Republic of)
	Northern America	Bermuda, Canada, Greenland, Saint Pierre and Miquelon, United States of America
ASIA		
	Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
	Eastern Asia	China, Hong Kong SAR, China, Macao SAR, China, mainland, China, Taiwan Province of, Democratic People's Republic of Korea, Japan, Mongolia, Republic of Korea
	South-eastern Asia	Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam
	Southern Asia	Afghanistan, Bangladesh, Bhutan, India, Iran (Islamic Republic of), Maldives, Nepal, Pakistan, Sri Lanka

TABLE A.2 (Continued)

Region	Subregion	Countries and territories
	Western Asia	Armenia, Azerbaijan, Bahrain, Cyprus, Gaza Strip (Palestine), Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, Türkiye, United Arab Emirates, Yemen, Yemen Ar Rp, Yemen Dem.
EUROPE		
	Eastern Europe	Belarus, Bulgaria, Czechia, Czechoslovakia, Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine, [USSR]
	Northern Europe	Åland Islands, Channel Islands, Denmark, Estonia, Faroe Islands, Finland, Guernsey, Iceland, Ireland, Isle of Man, Jersey, Latvia, Lithuania, Norway, Sark, Svalbard and Jan Mayen Islands, Sweden, United Kingdom of Great Britain and Northern Ireland
	Southern Europe	Albania, Andorra, Bosnia and Herzegovina, Croatia, Gibraltar, Greece, Holy See, Italy, Kosovo,* Malta, Montenegro, North Macedonia, Portugal, San Marino, Serbia, [Serbia and Montenegro], Slovenia, Spain, [Yugoslav SFR]
	Western Europe	Austria, Belgium, Belgium-Luxembourg, France, Germany, Liechtenstein, Luxembourg, Monaco, Netherlands (Kingdom of the), Switzerland
OCEANIA		
	Australia and New Zealand	Australia, Christmas Island, Cocos (Keeling) Islands, Heard Island and McDonald Islands, New Zealand, Norfolk Island
	Melanesia	Fiji, New Caledonia, Papua New Guinea, Solomon Islands, Vanuatu
	Micronesia	Guam, Kiribati, Marshall Islands, Micronesia (Federated States of), Nauru, Northern Mariana Islands, Pacific Islands Trust Territory, Palau, United States Minor Outlying Islands
	Polynesia	American Samoa, Cook Islands, French Polynesia, Niue, Pitcairn, Samoa, Tokelau, Tonga, Tuvalu, Wake Island, Wallis and Futuna Islands

NOTE: * Reference to Kosovo shall be understood to be in the context of Security Council resolution 1244 (1999).

SOURCE: Authors' own elaboration with regional and subregional aggregations based on FAO. 2025. FAOSTAT: Definitions and Standards. [Accessed on 7 May 2025]. https://www.fao.org/faostat/en/#definitions. Licence: CC-BY-4.0.

REFERENCES

CHAPTER 1

Agbeshie, A.A., Abugre, S., Atta-Darkwa, T. & Awuah, R. 2022. A review of the effects of forest fire on soil properties. *Journal of Forestry Research*, 33: 1419–1441. https://doi.org/10.1007/s11676-022-01475-4

Barreiro, A. & Díaz-Raviña, M. 2021. Fire impacts on soil microorganisms: Mass, activity, and diversity. *Current Opinion in Environmental Science & Health*, 22: 100264. https://doi.org/10.1016/j.coesh.2021.100264

Bezner Kerr, R., Hasegawa, T., Lasco, R., Bhatt, I., Deryng, D., Farrell, A., Gurney-Smith, H. *et al.* 2023. Food, Fibre, and Other Ecosystem Products. In: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig *et al.*, eds. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press. https://doi.org/10.1017/9781009325844.007

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y., Lissner, T.K. *et al.* 2022. Water. In: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig *et al.*, eds. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press. https://doi.org/10.1017/9781009325844.006

Doerr, S.H., Santín, C. & Mataix-Solera, J. 2023. Fire effects on soil. *Encyclopedia of Soils in the Environment*, 2: 448–457. https://doi.org/10.1016/B978-0-12-822974-3.00106-3

Donley, N., Cox, C., Bennett, K., Temki, A.M., Andrews, D.Q. & Naidenko, O.V. 2024. Forever Pesticides: A Growing Source of PFAS Contamination in the Environment. *Environmental Health Perspectives,* 132(7): 075003. https://doi.org/10.1289/EHP13954

EM-DAT. 2024. The International Disaster Database. [Accessed on 10 May 2025]. http://www.emdat.be. Licence: CC-BY-NC-ND.

FAO (Food and Agriculture Organization of the United Nations). 2005. *Statistical Yearbook of the Food and Agriculture Organization of the United Nations*. Rome. https://www.fao.org/4/i3107e/i3107e05.pdf

FAO. 2017. *The future of food and agriculture: Trends and challenges*. Rome. https://openknowledge.fao.org/items/ede32306-aeec-4891-9fe6-7e4f2fd93143

FAO. 2019. *The State of the World's Biodiversity for Food and Agriculture.* J. Bélanger & D. Pilling, eds. FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome. https://doi.org/10.4060/ca3129en

FAO. 2022a. *The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Main report*. Rome. https://doi.org/10.4060/cb9910en

FAO. 2022b. *FRA 2020 Remote Sensing Survey.* FAO Forestry Paper, No. 186. Rome. https://doi.org/10.4060/cb9970en

FAO. 2022c. *Framework for Action on Biodiversity for Food and Agriculture*. FAO Commission on Genetic Resources for Food and Agriculture. Rome. https://doi.org/10.4060/cb8338en

FAO. 2023a. *Agrifood systems and land-related emissions. Global, regional and country trends, 2001–2021*. FAOSTAT Analytical Briefs, No. 73. Rome. https://doi.org/10.4060/cc8543en

FAO. 2023b. *Gap analysis to support due diligence in the avocado and pineapple sectors.* Rome. https://doi.org/10.4060/cc4149en

FAO. 2023c. *Sand and dust storms – A guide to mitigation, adaptation, policy and risk management measures in agriculture.* Rome. https://doi.org/10.4060/cc8071en

FAO. 2023d. *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

FAO. 2024a. *Global status of salt affected soils. Main report*. Rome. https://doi.org/10.4060/cd3044en

FAO. 2024b. *Cropland nutrient balance – Global, regional and country trends, 1961–2022*. FAOSTAT Analytical Briefs, No. 95. Rome. https://openknowledge.fao.org/handle/20.500.14283/cd3164en

FAO. 2024c. *Pesticides use and trade – 1990–2022*. FAOSTAT Analytical Briefs, No. 89. Rome. https://doi.org/10.4060/cd1486en

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

FAO. 2025a. FAOSTAT: Fertilizers by nutrient. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/RFN. Licence: CC-BY-4.0.

FAO. 2025b. FAOSTAT: Bioenergy. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/BE. Licence: CC-BY-4.0.

FAO. 2025c. FAOSTAT: Temperature changes on land. [Accessed on 24 April 2025]. https://www.fao.org/faostat/en/#data/ET. Licence: CC-BY-4.0.

FAO. 2025d. *Temperature change statistics 1961–2024 – Global, regional and country trends*. FAOSTAT Analytical Briefs, No. 101. Rome. https://doi.org/10.4060/cd4714en

FAO & UNEP (United Nations Environment Programme). 2021. Global Assessment of Soil Pollution: Report. Rome, FAO. https://doi.org/10.4060/cb4894en

Giglio, L., Randerson, J.T., van der Werf, G.R., Kasibhatla, P.S., Collatz, G.J., Morton, D.C. & DeFries, R.S. 2010. Assessing variability and long-term trends in burned area by merging multiple satellite fire products. *Biogeosciences*, 7(3): 1171–1186. https://doi.org/10.5194/bg-7-1171-2010

IPCC (Intergovernmental Panel on Climate Change). 2019. Summary for Policymakers. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai *et al.*, eds. *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*. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/12/02_Summary-for-Policymakers_SPM.pdf

IPCC. 2023. Summary for Policymakers. In: H. Lee & J. Romero, eds. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

JRC (Joint Research Centre of European Commission). 2018. Joint Research Centre Data Catalogue: Burnt area in the Global Wildfire Information System (version 2-3-1). [Accessed on April 2025]. http://data.europa.eu/89h/e6f7a4e7-1f64-4ba9-9363-6bc864ab4666. Licence: CC-BY-4.0.

Lin, M. & Begho, T. 2022. Crop residue burning in South Asia: A review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses. *Journal of Environmental Management*, 314: 115104. https://www.sciencedirect.com/science/article/pii/S0301479722006776

Maggi, F., Tang, F.H. & Tubiello, F.N. 2023. Agricultural pesticide land budget and river discharge to oceans. *Nature*, 620: 1013–1017. https://doi.org/10.1038/s41586-023-06296-x

Ren, S., Wang, T., Guenet, B., Liu, D., Cao, Y., Ding, J. Smith, P. & Piao, S. 2024. Projected soil carbon loss with warming in constrained Earth system models. *Nature Communications*, 15(102): 1–10. https://doi.org/10.1038/s41467-023-44433-2

Rackelmann, F., Sparkes, E., Sabino Siemons, A.-S., Hashweh, D., Pineda Fernandez, D.M., Werners, S.E., Orr, B.J., Andreeva, O. & Walz, Y. 2024 *Promoting synergies between land degradation neutrality and climate change adaptation: A supplement to the National Adaptation Plan technical guidelines*. Bonn, Germany, UNCCD (United Nations Convention to Combat Desertification) & UNU-EHS (United Nations University Institute for Environment and Human Security). https://collections.unu.edu/view/UNU:10074

Raleigh, C., Kishi R., & Linke, A. 2023. Political instability patterns are obscured by conflict dataset scope conditions, sources, and coding choices. *Humanities & Social Sciences Communications*, 10(1): 1–17. https://www.nature.com/articles/s41599-023-01559-4.pdf

Seo, K.W., Ryu, D., Jeon, T., Youm, K., Kim, J.S., Oh, E. H. & Wilson, C.R. 2025. Abrupt sea level rise and Earth's gradual pole shift reveal permanent hydrological regime changes in the 21st century. *Science*, 387(6741): 1408–1413. https://www.science.org/doi/10.1126/science.adq6529

Smith, P., Poch, R.M., Lobb, D.A., Bhattacharyya, R., Alloush, G., Eudoxie, G.D., Anjos, L.H.C. *et al.* 2024. Status of the World's Soils. *Annual Review of Environment and Resources*, 49: 73–104. https://doi.org/10.1146/annurev-environ-030323-075629

Tang, F.H.M., Lenzen, M., McBratney, A. & Maggi, F. 2021. Risk of pesticide pollution at the global scale. *Nature Geoscience,* 14**:** 206–210. https://doi.org/10.1038/s41561-021-00712-5

UNCCD (**United Nations Convention to Combat Desertification)**. 2022a. *The Global Land Outlook.* Second edition. Bonn, Germany. https://www.unccd.int/resources/global-land-outlook/global-land-outlook-2nd-edition

UNCCD. 2022b. *Sand and dust storms compendium: Information and guidance on assessing and addressing the risks*. Bonn, Germany. https://www.unccd.int/resources/publications/sand-and-dust-storms-compendium-information-and-guidance-assessing-and

UNCCD. 2023. *Global Drought Snapshot 2023: The need for proactive action*. Bonn, Germany. https://www.unccd.int/sites/default/files/2023-12/Global%20drought%20snapshot%202023.pdf

UNCCD. n.d. UNCCD Data Dashboard: Land degradation and drought. [Accessed on 10 May 2025]. https://data.unccd.int. Licence: CC BY-NC 2.0.

UNEP. 2022. *Global Peatlands Assessment – The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands*. Main Report. Global Peatlands Initiative. Nairobi. https://www.unep.org/resources/global-peatlands-assessment-2022

UNEP & FAO. 2024. *Global Nitrous Oxide Assessment*. Nairobi. https://doi.org/10.59117/20.500.11822/46562

van Lierop, P., Lindquist, E., Sathyapala, S. & Franceschini, G. 2015. Global forest area disturbance from fire, insect pests, diseases and severe weather events. *Forest Ecology and Management*, 352: 78–88. https://doi.org/10.1016/j.foreco.2015.06.010

World Bank. 2025. DataBank: Metadata Glossary. [Accessed on 1 April 2025]. Licence: CC-BY-4.0. https://databank.worldbank.org/metadataglossary/africa-development-indicators/series/NY.GDP.MKTP.PP.KD#:~:text=An%20international%20dollar%20has%20the,the%20value%20of%20the%20products

Ziadat, F., Conchedda, G., Haddad, F., Njeru, J., Brès, A., Dawelbait, M. & Li, L. 2025. Desertification and Agrifood Systems: Restoration of Degraded Agricultural Lands in the Arab Region. *Agriculture*, 15(12): 1249. https://doi.org/10.3390/agriculture15121249

CHAPTER 2

FAO. 2020. *The State of Food and Agriculture 2020 – Overcoming water challenges in agriculture.* Rome. https://doi.org/10.4060/cb1447en

FAO. 2021. *The State of the World's Land and Water Resources for Food and Agriculture 2021 – Systems at breaking point. Synthesis report 2021*. Rome. https://doi.org/10.4060/cb7654en

FAO. 2025a. FAOSTAT: Land use. [Accessed on 1 July 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0.

FAO. 2025b. *Restoration of degraded agricultural lands – An urgent need for agrifood system transformation and land degradation neutrality*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/077ccd0e-44ff-48ab-9d3d-27de52eca005/content

FAO & IIASA (International Institute for Applied Systems Analysis). 2025a. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 1 July 2025]. https://www.fao.org/gaez/en

FAO & IIASA. 2025b. FAO Agro-Ecological Zoning: Share of land cover class (Global - ~1 km) – GAEZ v5. [Accessed on 13 February 2025]. https://data.apps.fao.org/catalog/iso/f7bee2f1-3a48-4e86-a1d2-387023dec046. Licence: CC-BY-4.0.

Tubiello, F.N., Conchedda, G., Casse, L., Hao, P., Chen, Z., De Santis, G., Fritz, S. & Muchoney, D. 2022. Zenodo: High resolution cropland agreement map (30 m) circa 2020 (v1.0). [Accessed on 24 April 2025]. https://doi.org/10.5281/zenodo.7244123. Licence: CC-BY-4.0.

Tubiello, F.N., Conchedda, G., Casse, L., Hao, P., Chen, Z., De Santis, G., Fritz, S. & Muchoney, D. 2023a. Measuring the world's cropland area. *Nature Food*, 4: 30–2. https://doi.org/10.13140/RG.2.2.25868.39041

Tubiello, F.N., Conchedda, G., Casse, L., Hao, P., De Santis, G. & Chen, Z. 2023b. A new cropland area database by country circa 2020. *Earth System Science Data,* 15: 4997–5015. https://doi.org/10.5194/essd-15-4997-2023

UNCCD. 2023. *Global Drought Snapshot 2023: The need for proactive action*. Bonn, Germany. https://www.unccd.int/sites/default/files/2023-12/Global%20drought%20snapshot%202023.pdf

Ziadat, F., Conchedda, G., Haddad, F., Njeru, J., Brès, A., Dawelbait, M. & Li, L. 2025. Desertification and Agrifood Systems: Restoration of Degraded Agricultural Lands in the Arab Region. *Agriculture*, 15(12): 1249. https://doi.org/10.3390/agriculture15121249

CHAPTER 3

Bardgett, R.D., Bullock, J.M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M. *et al.* 2021. Combatting global grassland degradation. *Nature Reviews Earth & Environment*, 2(10): 720-735. https://doi.org/10.1038/s43017-021-00207-2

Csikós, N. & Tóth, G. 2023. Concepts of agricultural marginal lands and their utilisation: A review. *Agricultural Systems*, 204(6): 103560. https://doi.org/10.1016/j.agsy.2022.103560

FAO. 2012. *Coping with water scarcity – An action framework for agriculture and food security.* FAO Water Report, No 38. Rome. https://openknowledge.fao.org/handle/20.500.14283/i3015e

FAO. 2020. *Position paper on "Ecosystem Restoration" of production ecosystems, in the context of the UN Decade of Ecosystem Restoration 2021-2030.* Document of the Twenty-seven Session of the FAO Committee on Agriculture (COAG 27). https://openknowledge.fao.org/server/api/core/bitstreams/4fd1f1d8-8109-4caa-a820-b99f0c09b3c8/content

FAO. 2022. *The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Main report.* Rome. https://doi.org/10.4060/cb9910en

FAO. 2025a. FAOSTAT: Land Use. Rome. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/RL. Licence: CC-BY-4.0.

FAO. 2025b. FAOSTAT: Crops and livestock products. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

FAO. (forthcoming). *Guidelines for integrated land-use planning – an update*. Rome.

FAO & IIASA. 2025a. *Global Agro-ecological Zoning version 5 (GAEZ v5) Model Documentation*. [Cited 13 February 2025]. https://www.fao.org/gaez/en

FAO & IIASA. 2025b. FAO Agro-Ecological Zoning: Share of land cover class (Global - ~1 km) – GAEZ v5. [Accessed on 13 February 2025. https://data.apps.fao.org/catalog/iso/f7bee2f1-3a48-4e86-a1d2-387023dec046. Licence: CC-BY-4.0.

FAO & UN-Water. 2024. *Progress on the level of water stress – Mid-term status of SDG Indicator 6.4.2 and acceleration needs, with special focus on food security, 2024*. Rome, FAO. https://doi.org/10.4060/cd2179en

Fischer, G., Hizsnyik, E., Prieler, S. & Wiberg, D. 2011. *Scarcity and abundance of land resources: competing uses and the shrinking land resource base.* SOLAW Background Thematic Report. Rome, FAO. https://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_02_light.pdf

Fischer, G., Nachtergaele, F.O., van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D. & Tramberend, S. 2021. *Global Agro-Ecological Zones – Model Documentation.* Rome, FAO. https://doi.org/10.4060/cb4744en

Gerber, J.S., Ray, D.K., Makowski, D., Butler, E.E., Mueller, N.D., West, P.C., Johnson, J.A. *et al.* 2024. Global spatially explicit yield gap time trends reveal regions at risk of future crop yield stagnation. *Nature Food*, 5: 125–135. https://doi.org/10.1038/s43016-023-00913-8

Guo, X., Zhang, P. & Yue, Y. 2024. Global wheat planting suitability under the 1.5 °C and 2 °C warming targets. *Frontiers in Plant Science*, 15: 1410388. https://doi.org/10.3389/fpls.2024.1410388

Habiba, U. & Abedin, M. 2024. *Impacts and Adaptation Measures of Climate Change on Agriculture in Coastal Bangladesh*. Oxford Research Encyclopedia of Natural Hazard Science. https://doi.org/10.1093/acrefore/9780199389407.013.416

IPCC. 2022. Summary for Policymakers. In: P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak *et al*., eds. *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press. https://doi.org/10.1017/9781009157926.001

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O., Faye, B. *et al.* 2021. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, 2(11): 873–885. https://doi.org/10.1038/s43016-021-00400-y

Mombo, V.-G., Duvallet, M., Schaeffer, M. & Baarsch, F. 2025. Have crops already reached peak suitability: Assessing global climatic suitability decreases for crop cultivation. *Environmental Research Letters*, 20(3): 034009. https://doi.org/10.1088/1748-9326/adacfe

Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., Hermans, K. *et al.* 2019. Land degradation. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai *et al*., eds. *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*. Cambridge, UK, Cambridge University Press. https://doi.org/10.1017/9781009157988.006

Ramankutty, N., Foley, J.A., Norman, J. & McSweeney, K. 2002. The global distribution of cultivable lands: Current patterns and sensitivity to possible climate change. *Global Ecology and Biogeogr*aphy, 11: 377–392. https://doi.org/10.1046/j.1466-822x.2002.00294.x

Ricardo, D. 1817. *On the principles of political economy and taxation.* London, J.M. Dent and Sons.

Sacande, M, Guarnieri, L., Maniatis, D., Marchi, G., Martucci, A., Mollicone, D., Morales, C., Oubida, W.R. & Sanchez Paus Diaz, A. 2022. *Africa Open Data for Environment, Agriculture and Land (DEAL) and Africa's Great Green Wall*. Rome, FAO. https://doi.org/10.4060/cc0725en

Thornton, P.K., van de Steeg, J., Notenbaert, A. & Herrero, M. 2009. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems*, 101(3): 113–127. https://doi.org/10.1016/j.agsy.2009.05.002

Tubiello, F.N., Conchedda, G., Casse, L., Hao, P., Chen, Z., De Santis, G., Fritz, S. & Muchoney, D. 2023a. Measuring the world's cropland area. *Nature Food*, 4: 30–32. https://doi.org/10.13140/RG.2.2.25868.39041

UNEP-WCMC (World Conservation Monitoring Centre) & IUCN (International Union for Conservation of Nature). 2022. Protected Planet. [Accessed on 24 March 2025]. https://www.protectedplanet.net/en. Licence: CC-BY-4.0.

Zabel, F., Putzenlechner, B. & Mauser, W. 2014. Global Agricultural Land Resources – A High Resolution Suitability Evaluation and Its Perspectives until 2100 under Climate Change Conditions. *PloS ONE*, 9(9): 107522. https://doi.org/10.1371/journal.pone.0114980

CHAPTER 4

Abate, T., Fisher, M., Abdoulaye, T., Kassie, G.T., Lunduka, R., Marenya, P. & Asnake, W. 2017. Characteristics of maize cultivars in Africa: How modern are they and how many do smallholder farmers grow? *Agriculture & Food Security*, 6(1): 30. https://doi.org/10.1186/s40066-017-0108-6

Agouridis, C.T., Workman, S.R., Warner, R.C. & Jennings, G.D. 2005. Livestock grazing management impacts on stream water quality: a review. *Journal of the American Water Resources Association*, 41(3): 591–606. https://doi.org/10.1111/j.1752-1688.2005.tb03757.x

Agrocomposta. 2021. *Agrocompostaje en Comunidad de Madrid*. [Cited 24 August 2024]. https://agrocomposta.org

Altieri, M.A. & Nicholls, C.I. 2018. Agroecología urbana: diseño de granjas urbanas ricas en biodiversidad, productivas y resilientes. *Agro Sur*, 46(2): 49–60. https://doi.org/10.4206/agrosur.2018.v46n2-07

Aquilani, C., Confessore, A., Bozzi, R., Sirtori, F. & Pugliese, C. 2022. Review: Precision Livestock Farming technologies in pasture-based livestock systems. *Animal*, 16(1): 100429. https://doi.org/10.1016/j.animal.2021.100429

Barral, M.P., Rey Benayas, J.M., Meli, P. & Maceira, N.O. 2015. Quantifying the impacts of ecological restoration on biodiversity and ecosystem services in agroecosystems: A global meta-analysis. *Agriculture, Ecosystems & Environment*, 202: 223–231. https://doi.org/10.1016/j.agee.2015.01.009

Barrios, E., Coe, R., Place, F., Sileshi, G. W. & Sinclair, F. 2023. *Nurturing Soil Life through Agroforestry.* Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/cc9088en

Beacham, A.M., Vickers, L.H. & Monaghan, J.M. 2019. Vertical farming: a summary of approaches to growing skywards. *The Journal of Horticultural Science and Biotechnology*, 94(3): 277–283. https://doi.org/10.1080/14620316.2019.1574214

Burt, C.M., Howes, D.J. & Mutziger, A. 2001*.* Evaporation Estimates for Irrigated Agriculture in California. *Conference Proceedings of the Annual Irrigation Association meeting*, ITRC Paper P01-002. https://www.researchgate.net/publication/228465121

Butturini, M. & Marcelis, L.F.M. 2020. Vertical farming in Europe: Present status and outlook. In: T. Kozai, G. Niu & M. Takagakipp, eds. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality food production*, pp. 77–91. Amsterdam, Kingdom of the Netherlands, Elsevier. https://doi.org/10.1016/B978-0-12-816691-8.00004-2

Cancela, J.J., González, X.P., Vilanova, M. & Mirás-Avalos, J.M. 2019. Water Management Using Drones and Satellites in Agriculture. *Water*, 11(5): 874. https://doi.org/10.3390/w11050874

Centeri, C. 2022. Effects of Grazing on Water Erosion, Compaction and Infiltration on Grasslands. *Hydrology*, 9(2): 34. https://doi.org/10.3390/hydrology9020034

Clinton, N., Stuhlmacher, M., Miles, A.,Uludere, N., Wagner, M., Georgescu, M., Herwig, C. & Gong, P. 2018. A Global Geospatial Ecosystem Services Estimate of Urban Agriculture. *Earth's Future*, 6: 40–60. https://doi.org/10.1002/2017EF000536

Coates, D. 2023. *Ecosystem restoration and inland food fisheries in developing countries – opportunities for United Nations Decade on Ecosystem Restoration (2021–2023).* FAO Fisheries and Aquaculture Circular, No. 1231. Rome, FAO. https://doi.org/10.4060/cc7082en

Coates, D., Arthur, R., Bennett, A., Gondwe, E., Shrestha, R. & Valbo-Jørgensen, J. 2025. *The role and potential of inland fisheries in low-emission food production and climate change mitigation*. FAO Fisheries and Aquaculture Circular, No. 1284. Rome, FAO. https://doi.org/10.4060/cd4601en

Dhakal, M., West, C.P., Villalobos, C., Brown, P. & Green, P.E. 2020. Interseeding alfalfa into native grassland for enhanced yield and water use efficiency. *Agronomy Journal*, 112(3): 1931–1942. https://doi.org/10.1002/agj2.20147

Díaz De Otálora, X., Epelde, L., Arranz, J., Garbisu, C., Ruiz, R. & Mandaluniz, N. 2021. Regenerative rotational grazing management of dairy sheep increases springtime grass production and topsoil carbon storage. *Ecological Indicators*, 125: 107484. https://doi.org/10.1016/j.ecolind.2021.107484

Döbert, T.F., Bork, E.W., Apfelbaum, S., Carlyle, C.N., Chang, S.X., Khatri-Chhetri, U., Silva Sobrinho, L., Thompson, R. & Boyce, M.S. 2021. Adaptive multi-paddock grazing improves water infiltration in Canadian grassland soils. *Geoderma*, 401: 115314. https://doi.org/10.1016/j.geoderma.2021.115314

FAO. 1998. *Modernization of irrigation system operations. Proceedings of the 5th ITIS network international meeting, Aurangabad, 28-30 October 1998.* Rome. https://www.fao.org/4/X6626E/x6626e00.htm#TopOfPage

FAO. 2015. *Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication.* Rome. https://openknowledge.fao.org/server/api/core/bitstreams/edfffbfc-81e5-4208-a36f-334ff81ac10f/content

FAO. 2019. *Ecosystem approach to fisheries management training course (Inland fisheries) – Volume 1: Handbook for trainees*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/341bda85-3c16-4eb3-b789-d2c9d2b7522a/content

FAO. 2020a. Family Farming Knowledge Platform – Labour-saving technologies and practices: raised beds. In: *FAO*. [Cited 21 May 2025]. https://www.fao.org/family-farming/detail/en/c/1619238

FAO. 2020b. *The State of Food and Agriculture 2020 – Overcoming water challenges in agriculture.* Rome. https://doi.org/10.4060/cb1447en

FAO. 2021. *Ecosystem approach to aquaculture management – Handbook*. Yangon, Myanmar. https://doi.org/10.4060/ca7972en

FAO. 2022a. *The State of the World's Forests 2022 – Forest pathways for green recovery and building inclusive, resilient and sustainable economies*. Rome. https://doi.org/10.4060/cb9360en

FAO. 2022b. *FRA 2020 Remote Sensing Survey*. FAO Forestry Paper, No. 186. Rome. https://doi.org/10.4060/cb9970en

FAO. 2022c. *The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Main report*. Rome. https://doi.org/10.4060/cb9910en

FAO. 2022d. *Evaluation of the project "Action Against Desertification in support of the implementation of the Great Green Wall for the Sahara and the Sahel Initiative, the United Nations to Combat Desertification and Drought action plans in Fiji and Haiti, and South–South cooperation in the African, Caribbean and Pacific Group of States".* Project Evaluation Series, No. 05/2022. Rome. https://openknowledge.fao.org/items/2b52f96e-4331-492b-99d0-4879b97769fe

FAO. 2022e. *Biodiversity for food and agriculture* [infographic]. Rome. https://openknowledge.fao.org/handle/20.500.14283/cc0045en

FAO. 2022f. *Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security*. First revision. Rome. https://doi.org/10.4060/i2801e

FAO. 2023. *Hydroponics systems for smallholder vegetable production.* Technical Fact Sheet, No. 13. https://openknowledge.fao.org/server/api/core/bitstreams/b920e1ae-feed-43e4-b64e-4e73a1a48a1d/content

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

FAO. 2024b. *Restoration of degraded agricultural lands*. Rome. https://openknowledge.fao.org/handle/20.500.14283/cd3109en

FAO. 2024c. *The State of the World's Forests 2024 – Forest-sector innovations towards a more sustainable future*. Rome. https://doi.org/10.4060/cd1211en

FAO. 2024d *Guidelines for Sustainable Aquaculture*. FAO Committee on Fisheries, Thirty-sixth Session, July 2024. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/b87a56eb-749d-4e76-b952-413708c021e0/content

FAO. 2025a. Global Partnership Initiative for Plant Breeding Capacity Building. In: *FAO*. [Cited 1 August 2025]. https://www.fao.org/in-action/plant-breeding/zh

FAO. 2025b. *Resilience and behaviour change assessment in Malawi in the districts of Mangochi, Ntcheu and Balaka*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/73bb131e-642e-4499-abb8-85267162abff/content

FAO, IUFRO (International Union of Forest Research Organizations) & USDA (US Department of Agriculture). 2021. *A guide to forest–water management.* FAO Forestry Paper, No. 185. Rome. https://doi.org/10.4060/cb6473en

FAO, Rikolto & RUAF (Resource Centre for Urban Agriculture and Food Security). 2022. *Urban and peri-urban agriculture sourcebook – From production to food systems*. Rome, FAO and Rikolto. https://doi.org/10.4060

FAO, Duke University & WorldFish. 2023. *Illuminating Hidden Harvests – The contributions of small-scale fisheries to sustainable development.* Rome, FAO. https://doi.org/10.4060/cc6062en

FAO & AfDB (African Development Bank). 2024. *Review of the state of world fishery resources – Inland fisheries.* FAO Fisheries and Aquaculture Circular, No. 942, Rev. 4. Rome and Abidjan. https://doi.org/10.4060/cd2169en

Fayezizadeh, M.R., Ansari, N.A.Z., Albaji, M. & Khakeghi, E. 2021. Effects of hydroponic systems on yield, water productivity and stomatal gas exchange of greenhouse tomato cultivars. *Agricultural Water Management*, 258(1): 107171. https://doi.org/10.1016/j.agwat.2021.107171

Fofana, B, Sacande, M., Blagna, F., Dibloni, T.O., Compaore, E., Sanon, K.B., Maiga, Y. & Ouattara, A.S. 2020. Boosting land restoration success in the Great Green Wall through the use of symbiotic microorganisms for propagated tree seedlings. *International Journal of Biological and Chemical Sciences*, 14(1). https://doi.org/10.4314/ijbcs.v14i1.10

Goliński, P., Sobolewska, P., Stefańska, B. & Golińska, B. 2022. Virtual Fencing Technology for Cattle Management in the Pasture Feeding System – A Review. *Agriculture*, 13(1): 91. https://doi.org/10.3390/agriculture13010091

Gregory, R., Funge-Smith, S.J. & Baumgartner, L. 2018. *An ecosystem approach to promote the integration and coexistence of fisheries within irrigation systems*. FAO Fisheries and Aquaculture Circular, No. 1169. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/fd375848-3a3f-4ec7-a6bc-9d1a3948018e/content

Guo, X., Zhou, H., Dai, L., Li, J., Zhang, F., Li, Y., Lin, L. *et al.* 2021. Restoration of Degraded Grassland Significantly Improves Water Storage in Alpine Grasslands in the Qinghai-Tibet Plateau. *Frontiers in Plant Science*, 12: 778656. https://doi.org/10.3389/fpls.2021.778656

Hartmann, L., Hansohm, J., Vellozo, L., Walinder, E., Orr, B.J., Andreeva, O. & Walz, Y. 2024. *The contribution of land and water management approaches to Sustainable Land Management and achieving Land Degradation Neutrality*. Bonn, Germany, UNU-EHS. https://collections.unu.edu/eserv/UNU:9640/Align_LDN_-_Webpdf.pdf

Hulvey, K.B., Mellon, C.D. & Kleinhesselink, A.R. 2021. Rotational grazing can mitigate ecosystem service trade-offs between livestock production and water quality in semi-arid rangelands. *Journal of Applied Ecology*, 58(10): 213–252. https://doi.org/10.1111/1365-2664.13954

Ickowitz, A., McMullin, S., Rosenstock, T.S., Dawson, I.K., Rowland, D., Powell, B., Mausch, K. *et al.* 2022. Transforming food systems with trees and forests. *The Lancet Planetary Health,* 6(7): e632–e639. https://doi.org/10.1016/S2542-5196(22)00091-2

Jepson, W., Stellbauer, M. & Thomson, P. 2023. *Revaluing multiple-use water services for food and water security*. FAO Land and Water Discussion Paper, No. 19. Rome, FAO. https://doi.org/10.4060/cc7317en

Jones, J.B. 2014. *Complete Guide for Growing Plants Hydroponically*. First edition. Boca Raton, USA, CRC Press. https://doi.org/10.1201/b16482

Kamran, M., Yan, Z., Jia, Q., Chang, S., Ahmad, I., Ghani, M.U. & Hou, F. 2022. Irrigation and nitrogen fertilization influence on alfalfa yield, nutritive value, and resource use efficiency in an arid environment. *Field Crops Research*, 284: 108587. https://doi.org/10.1016/j.fcr.2022.108587

Kassam, A., Friedrich, T. & Derpsch, R. 2022. Successful Experiences and Lessons from Conservation Agriculture Worldwide. *Agronomy*, 12(4): 769. https://doi.org/10.3390/agronomy12040769

Lages Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G.M. & Halden, R.U. 2015. Comparison of Land, Water, and Energy Requirements of lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health*, 12(6): 6879–6891. https://doi.org/10.3390/ijerph120606879

Lai, L. & Kumar, S. 2020. A global meta-analysis of livestock grazing impacts on soil properties. *PLoS ONE*, 15(8): e0236638. https://doi.org/10.1371/journal.pone.0236638

Laird, S., Muir, G., Shanley, P., Pierce, A., López Binnquist, C., de Beer, J., Vinceti, B. & Walter, S. 2024. *Forests, trees and wild species in agrifood systems – Optimizing benefits for biodiversity, climate and health*. Rome, FAO. https://doi.org/10.4060/cd2883en

Lelièvre, F. & Volaire, F. 2009. Current and Potential Development of Perennial Grasses in Rainfed Mediterranean Farming Systems. *Crop Science*, 49(6): 2371–2378. https://doi.org/10.2135/cropsci2009.06.0324

Liu, Y., Guo, L., Huang, Z., López-Vicente, M. & Wu, G.-L. 2020. Root morphological characteristics and soil water infiltration capacity in semi-arid artificial grassland soils. *Agricultural Water Management*, 235: 106153. https://doi.org/10.1016/j.agwat.2020.106153

Lüscher, A., Barkaoui, K., Finn, J.A., Suter, D., Suter, M. & Volaire, F. 2022. Using plant diversity to reduce vulnerability and increase drought resilience of permanent and sown productive grasslands. *Grass and Forage Science*, 77(4): 235–246. https://doi.org/10.1111/gfs.12578

MAAIF (Ministry of Agriculture, Animal Industry and Fisheries). 2023. *National plan of action for implementation of the voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication (NPOA-SSF) in Uganda*. Republic of Uganda. https://www.fao.org/fileadmin/user_upload/ssf/documents/npoa_uganda.pdf

Mekonnen, T.W., Mekbib, F., Amsalu, B., Gedil, M. & Labuschagne, M. 2022. Genotype by environment interaction and grain yield stability of drought tolerant cowpea landraces in Ethiopia. *Euphytica*, 218(5): 57. https://doi.org/10.1007/s10681-022-03011-1

Minnemeyere, S., Laestadius, L. & Sizer, N. 2011. *A world of opportunity*. World Resource Institute. http://pdf.wri.org/world_of_opportunity_brochure_2011-09.pdf

Muchane, M.N., Sileshi, G.W., Gripenberg, S., Jonsson, M., Pumariño, L. & Barrios, E. 2020. Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. *Agriculture, Ecosystems & Environment*, 295: 106899. https://doi.org/10.1016/j.agee.2020.106899

Muir, G.F., Sorrenti, S., Vantomme, P., Vidale, E., & Masiero, M. 2020. Into the wild: disentangling non-wood terms and definitions for improved forest statistics. *International Forestry Review*, 22*(*1): 101–119. https://openknowledge.fao.org/handle/20.500.14283/ca9347en

Ngaba, J., Mgelwa, A., Gurmesa, G.A., Uwiragiye, Y., Zhu, F., Qiu, Q., Fang, Y., Hu, B. & Rennenberg, H. 2023. Meta-analysis unveils differential effects of agroforestry on soil properties in different zonobiomes. *Plant and Soil,* 496(1): 1–19. https://doi.org/10.1007/s11104-023-06385-w

Pahlow, M., van Oel, P.R., Mekonnen, M.M. & Hoekstra, A.Y. 2015. Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. *Science of The Total Environment*, 536: 847–857. https://doi.org/10.1016/j.scitotenv.2015.07.124

Pastorelli, G., Serra, V., Vannuccini, C. & Attard, E. 2022. *Opuntia* spp. as alternative fodder for sustainable livestock production. *Animals*, 12(13): 1597. https://doi.org/10.3390/ani12131597

Pek, E. 2022. *The PRISM tool – Prioritization of irrigation schemes for modernization/rehabilitation*. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/300d5a5f-a773-4f7d-9589-0c2892b0171e/content

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T & van Kessel, C. 2015. Productivity limits and potentials of the principles of conservation agriculture. *Nature*, 517: 365–368. https://doi.org/10.1038/nature13809

Playán, E., Gimeno, Y., Lorenzo-González, M.A., Jiménez, A., López-Pardo, J.R., Oliván, I., Castillo, R. *et al.* 2024. Irrigation modernization in the Ebro – Aragón region of Spain: Past and future trends. *Agricultural Water Management*, 302: 108975. https://doi.org/10.1016/j.agwat.2024.108975

Pumariño, L., Sileshi, G.W., Gripenberg, S., Kaartinen, R., Barrios, E., Muchane, M.N., Midega, C. & Jonsson, M. 2015. Effects of agroforestry on pest, disease and weed control: A meta-analysis. *Basic and Applied Ecology*, 16(7): 573–582. https://doi.org/10.1016/j.baae.2015.08.006

Resh, H.M. 2022. *Hydroponic Food Production: A Definitive guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower.* Eighth edition. Boca Raton, USA, CRC Press. https://doi.org/10.1201/9781003133254

RUAF. 2017. Urban Agroecology. *Urban Agriculture Magazine*, No. 33. https://ruaf.org/document/urban-agriculture-magazine-no-33-urban-agroecology

Sacande, M., Parfondry, M. & Cicatiello, C. 2019. *Restoration in Action Against Desertification: A manual for large-scale restoration to support rural communities' resilience in Africa's Great Green Wall*. Rome, FAO. https://doi.org/10.4060/ca6932en

Sacande, M. & Muir, G. 2022. Restoring Food Systems with Nutritious Native Plants: Experiences from the African Drylands. *Food and Nutrition Bulletin*, 44(2): S58–S68. https://doi.org/10.1177/03795721231190779

Shaw, B.J. 2017. Østergro Rooftop Farm – Community Supported Agriculture in the Middle of Copenhagen. In: C. Bieling & T. Plieninger, eds. *The Science and Practice of Landscape Stewardship.* Cambridge, UK, Cambridge University Press. https://doi.org/10.1017/9781316499016.026

Shepherd, M., Nichols, S. & Selbie, D. 2021. An assessment of the role of soil organic matter in pasture resilience. *NZGA: Research and Practice Series*, 17: 179–190. https://doi.org/10.33584/rps.17.2021.3469

Smith, K. & Elgersma, A. 2021. Editorial – Annual and perennial forage legumes in dryland pasture systems. *Grass and Forage Science*, 76(1): 1–2. https://doi.org/10.1111/gfs.12529

Stoner, S.W., Hoyt, A.M., Trumbore, S., Sierra, C.A., Schrumpf, M., Doetterl, S., Baisden, W.T. & Schipper, L.A. 2021. Soil organic matter turnover rates increase to match increased inputs in grazed grasslands. *Biogeochemistry*, 156(1): 145–160. https://doi.org/10.1007/s10533-021-00838-z

Taleb, M.H., Majidi, M.M., Pirnajmedin, F. & Maibody, S.A.M.M. 2023. Plant functional trait responses to cope with drought in seven cool-season grasses. *Scientific Reports*, 13(1): 5285. https://doi.org/10.1038/s41598-023-31923-y

Teague, R. & Kreuter, U. 2020. Managing Grazing to Restore Soil health, Ecosystem Function, and Ecosystem Services. *Frontiers in Sustainable Food Systems*, 4: 534187. https://doi.org/10.3389/fsufs.2020.534187

Udawatta, P.R., Rankoth, L. & Jose, S. 2019. Agroforestry and Biodiversity. *Sustainability*, 11(10): 2879. https://doi.org/10.3390/su11102879

van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E. *et al.* 2021. Current status and future challenges in implementing and upscaling vertical farming systems. *Nature Food*, 2(12): 944–956. https://doi.org/10.1038/s43016-021-00402-w

Wang, L., Ning, S., Zheng, W., Guo, J., Li, Y., Li, Y., Chen, X., Ben-Gal, A. & Wei, X. 2023. Performance analysis of two typical greenhouse lettuce production systems: Commercial hydroponic production and traditional soil cultivation. *Frontiers in Plant Science*, 14: 1165856. https://doi.org/10.3389/fpls.2023.1165856

Wisser, D., Grogan, D.S., Lanzoni, L., Tempio, G., Cinardi, G., Prusevich, A. & Glidden, S. 2024. Water Use in Livestock agri-Food Systems and Its Contribution to Local Water Scarcity: A Spatially Distributed Global Analysis. *Water*, 16(12): 1681. https://doi.org/10.3390/w16121681

Xu, R., Shi, W., Kamran, M., Chang, S., Jia, Q. & Hou, F. 2023. Grass-legume mixture and nitrogen application improve yield, quality, and water and nitrogen utilization efficiency of grazed pastures in the loess plateau. *Frontiers in Plant Science*, 14. https://doi.org/10.3389/fpls.2023.1088849

Zomer, R.J., Antonio, T., Richard, C., Frank, P., Meine van, N. & Jianchu, X. 2009. *Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics*. Working Paper, No. 179. Bogor, Indonesia, World Agroforestry Centre. https://apps.worldagroforestry.org/downloads/Publications/PDFS/WP14064.pdf

CHAPTER 5

Agarwal, A., delos Angeles, M.S., Bhatia, R., Chéret, Davila-Poblete, S., Falkenmark, M., Villarreal, F.G. *et al.* 2000. *Integrated Water Resources Management*. TAC Background Papers, No. 4. Stockholm, Global Water Partnership. https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04-integrated-water-resources-management-2000-english.pdf

Al'Afghani, M, Văn Chính, L. & Hodgson, S. 2024. Asia-Pacific Region: Water tenure scoping studies in Indonesia and Viet Nam. In: S. Hodgson, V. Gillet, S. Espinosa Flor, S. Ramirez Fionda, B. Kiersch & D. Vallée, eds. 2024. *Water tenure perspectives – Proceedings of the Water Tenure Mondays webinar series*. Rome, FAO. https://doi.org/10.4060/cd2941en

Bastin, J.-F., Finegold, Y., Garcia, C.A., Mollicone, D., Rezende, M., South, D., Zohner, C.M. & Crowther, T.W. 2019. The global tree restoration potential. *Science*, 365(6448): 76–79. https://www.science.org/doi/10.1126/science.aax0848

Batchelor, C., Hoogeveen, J., Faures, J.M. & Peiser, L. 2016. *Water accounting and auditing. A sourcebook*. FAO Water Report, No. 43. Rome, FAO. https://www.fao.org/3/a-i5923e.pdf

Bojić, D., Clark, M. & Urban, K. 2022. *Focus on governance for more effective policy and technical support.* Governance and policy support framework paper. Rome, FAO. https://doi.org/10.4060/cc0240en

Buchhorn, M., Bertels, L., Smets, B., De Roo, B., Lesiv, M., Tsendbazar, N.E., Masiliunas, D. & Li, L. 2020a. Algorithm theoretical basis document. In: *Copernicus Land Monitoring Service (2015): Land Cover 2015-2019 (raster 100 m)*. https://doi.org/10.2909/c6377c6e-76cc-4d03-8330-628a03693042

Buchhorn, M., Lesiv, M., Erdene Tsendbazar, N., Herold, M., Bertels, L. & Smets, B. 2020b. Copernicus Global Land Cover Layers—Collection 2. *Remote Sens*ing, 12(6): 1044. https://doi.org/10.3390/rs12061044

Cabell, J.F. & Oelofse, M. 2012. An Indicator Framework for Assessing Agroecosystem Resilience. *Ecology and Society*, 17(1): 18. https://www.jstor.org/stable/26269017

CBD (Convention on Biological Diversity). 2018. *The Pan-African Action Agenda on Ecosystem Restoration for increased Resilience*. Montreal, Canada. https://www.cbd.int/doc/c/274b/80e7/34d341167178fe08effd0900/cop-14-afr-hls-04-final-en.pdf

CBD. 2022. *Kunming–Montreal Global Biodiversity Framework (CBD/COP/DEC/15/4)*. Montreal, Canada, CBD Secretariat. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

CGIAR. n.d. Amplifying CGIAR impact with higher innovation readiness and use. In: *CGIAR*. [Cited 11 June 2025]. https://www.cgiar.org/portfolio-narrative/action-area-focus/regional-integrated-initiatives/#:~:text=For20example2C20the20CGIAR20Initiative20on20Diversification,million20people20that20watch20the20show20weekly

Cotula, L. & Knight, R. 2021. *Protecting legitimate tenure rights: From concepts to practice*. Legal Brief, No. 2. Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/cb4489en

Davies, F. 2015. *Analytical assessment report for the implementation of the Voluntary Guidelines on Responsible Governance of Tenure in the land, fisheries and forestry sectors of Sierra Leone*. FAO Legal Papers, No. 96. Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/i5193e

Davis, B., de la O Campos, A.P., Farrae, M. & Winters, P. 2024. Whither the agricultural productivity-led model? Reconsidering resilient and inclusive rural transformation in the context of agrifood systems. *Global Food Security*, 43: 100812. https://doi.org/10.1016/j.gfs.2024.100812

Deininger, K., Selod, H. & Burns, A. 2012. *The land governance assessment framework: identifying and monitoring good practice in the land sector*. Washington, DC, World Bank. http://documents.worldbank.org/curated/en/862461468327558327

Deutz, A., Heal, G.M., Niu, R., Swanson, E., Townshend, T., Zhu, L., Delmar, A., Meghji, A., Sethi, S. A. & Tobinde la Puente, J. 2020. *Financing nature: Closing the global biodiversity financing gap*. The Paulson Institute, The Nature Conservancy and the Cornell Atkinson Center for Sustainability. https://doi.org/10.13140/RG.2.2.26226.32968

EIB (European Investment Bank). n.d. *Investing in nature: Financing conservation and nature-based solutions*. A Practical Guide for Europe including how to access support from the European Investment Bank's dedicated Natural Capital Financing Facility. Luxembourg. https://www.eib.org/attachments/pj/ncff-invest-nature-report-en.pdf

Espinosa, S. & Kiersch, B. 2024. The benefits of a water tenure perspective: Knowledge from a pilot exercise in Rwanda, Senegal and Sri Lanka. In: S. Hodgson, V. Gillet, S. Espinosa Flor, S. Ramirez Fionda, B. Kiersch & D. Vallée, eds. *Water tenure perspectives – Proceedings of the Water Tenure Mondays webinar series.* Rome, FAO. https://doi.org/10.4060/cd2941en

FAO. 2016a. *Responsible governance of tenure and the law – A guide for lawyers and other legal service providers*. Governance of Tenure Technical Guide, No. 5. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/62029425-d044-4a47-8295-15ad62222b3a/content

FAO. 2016b. *Exploring the concept of water tenure*. Rome. http://www.fao.org/3/i5435e/i5435e.pdf

FAO. 2017a. *Land resource planning for sustainable land management – Current and emerging needs in land resource planning for food security, sustainable livelihoods, integrated landscape management and restoration*. Land and Water Division Working Paper, No 14. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/710fc58f-00c6-4855-b4ea-c455048bd49f/content

FAO. 2017b. *Sustainable Land Management (SLM) in practice in the Kagera Basin – Lessons learned for scaling up at landscape level.* Results of the Kagera Transboundary Agro-ecosystem Management Project (Kagera TAMP). Rome. https://openknowledge.fao.org/handle/20.500.14283/i6085e

FAO. 2018. *Sustainable food systems: Concept and framework*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/b620989c-407b-4caf-a152-f790f55fec71/content

FAO. 2019. *Disaster risk reduction at farm level: Multiple benefits, no regrets*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/7ac8df23-ca71-4e25-ab3a-b7411b14393c/content

FAO. 2020. *Unpacking water tenure for improved food security and sustainable development.* Land and Water Discussion Papers. Rome. https://doi.org/10.4060/cb1230en

FAO, UNDP & UNEP. 2021. *A multi-billion-dollar opportunity – Repurposing agricultural support to transform food systems*. In brief. Rome. https://doi.org/10.4060/cb6683en

FAO. 2022a. *Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security.* First revision. Rome. https://doi.org/10.4060/i2801e

FAO. 2022b. *Governance of tenure of water resources for food and agriculture*. FAO Committee on Agriculture, COAG/2022/15. Rome. https://www.fao.org/3/nj011en/nj011en.pdf

FAO. 2022c. *Report of the 28th Session of the Committee on Agriculture, Rome, 18–22 July 2022*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/e9afa285-7dd8-44e7-a606-e16a6ad9181e/content

FAO. 2023a. *UN 2023 Water Conference Side Event – National Water Roadmaps towards the 2030 Agenda, 22 March 2023*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/249799bf-8013-4cf9-9f04-9feaa73f0b9a/content

FAO. 2023b. *The State of Food and Agriculture: Integrated Water Resources Management.* Forty-third Session of the Conference, Rome, 1–7 July 2023. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/efc7f055-1c0a-485c-9b2a-fef65ee2ef21/content

FAO. 2023c. Harnessing *the potential of the 10 Elements of Agroecology to facilitate agrifood systems transformation – From visual narratives to integrated policy design.* Rome. https://doi.org/10.4060/cc4049en

FAO. 2023d. *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

FAO. 2024a. *Ministerial Declaration on managing water scarcity and reversing soil degradation for sustainable and resilient agrifood systems*. International Soil and Water Forum 2024, 9–11 December 2024, Bangkok. Rome. https://openknowledge.fao.org/items/cf23366f-c14e-4eb5-b88b-f29d27fb3661

FAO. 2024b. *Water auditing/water governance analysis – Governance and policy support: Methodological framework.* Rome. https://doi.org/10.4060/cc8993en

FAO. 2024c. *Promoting water tenure for food security, climate resilience and equity – Workshop report*. Rome. https://doi.org/10.4060/cd0222en

FAO. 2025a. *Transforming food and agriculture through a systems approach*. Rome.

FAO. 2025b. *FAO Conceptual Framework for Integrated Land and Water Resources Management.* Rome. https://openknowledge.fao.org/items/150d29a2-8b0e-43fe-a060-24b70f56e38b

FAO. (forthcoming). *FAO guidelines for integrated land-use planning – an update*. Rome.

FAO & AfDB. 2024. *Review of the state of world fishery resources – Inland fisheries.* FAO Fisheries and Aquaculture Circular, No. 942, Rev. 4. Rome and Abidjan. https://doi.org/10.4060/cd2169en

FAO & UNCCD. 2022. *Technical Guide on the integration of the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the context of national food security into the implementation of the United Nations Convention to Combat Desertification and Land Degradation Neutrality.* Rome and Bonn, Germany. https://doi.org/10.4060/cb9656en

FAO & UNCCD. 2024. *UNCCD-FAO Initiative on land tenure*. Rome. https://openknowledge.fao.org/handle/20.500.14283/cd3498en

FAO, IUCN, CEM (Commission on Ecosystem Management) & SER (Society for Ecological Restoration). 2021. *Principles for ecosystem restoration to guide the United Nations Decade 2021–2030.* Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/b234f058-9f77-4481-b870-a7fa2e7ad5f8/content

Ghosh, E., Kemp-Benedict, E., Huber-Lee, A., Nazareth, A. & Oudra, I. 2022. *Investing in agricultural, water, sustainably – Recent trends in financing institutions*. FAO Investment Centre – Directions in Investment, No. 7. Rome, FAO. https://doi.org/10.4060/cc1212en

Gliessman, S. 2007. *Agroecology: The ecology of sustainable food systems.* Second edition. Boca Raton, USA, CRC Press.

Gliessman, S. 2018. Defining Agroecology. *Agroecology and Sustainable Food Systems*, 42(6). https://doi.org/10.1080/21683565.2018.1432329

Hernández Lagana, M., Phillips, S. & Poisot, A. 2022. *Self-evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists (SHARP+) – A new guidance document for practitioners*. Rome, FAO. https://doi.org/10.4060/cb7399en

Hodgson, S., Gillet, V., Espinosa Flor, S., Ramirez Fionda, S., Kiersch, B. & Vallée, D., eds. 2024. *Water tenure perspectives – Proceedings of the Water Tenure Mondays webinar series.* Rome, FAO. https://doi.org/10.4060/cd2941en

Hodgson, S., Rothe, A.-K., Espinosa Flor, S., Troell, J. & Kiersch, B. 2024. *Water tenure assessment.* Rome, FAO. https://doi.org/10.4060/cd1853en

Huber-Lee, A., Kemp-Benedict, E., Gosh, E., Nazareth, A. & Oudra, I. 2021. *Investing in agricultural water management – Pathways to a sustainable future.* Rome, FAO. https://doi.org/10.4060/cb8059en

IDH (Sustainable Trade Initiative). 2021. *Inclusive investments in sustainable land management to help achieve land degradation neutrality. New insights from the Land Degradation Neutrality Fund and Technical Assistance Facility.* Learning brief. Utrecht, Kingdom of the Netherlands, IDH, Mirova, UNCCD, AFD, WWF & GEF. https://www.idhsustainabletrade.com/uploaded/2021/03/2020-LDN-Report-10.5-Large.pdf

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2018. *The IPBES assessment report on land degradation and restoration*. Bonn, Germany, Secretariat of IPBES. https://files.ipbes.net/ipbes-web-prod-public-files/2018_ldr_full_report_book_v4_pages.pdf

IPCC. 2019. Summary for Policymakers. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai *et al.*, eds. *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*. Cambridge University Press. https://doi.org/10.1017/9781009157988.001

IPCC. 2022. Summary for Policymakers. In: P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak *et al*., eds. *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press. https://doi.org/10.1017/9781009157926.001

LPFN (Landscapes for People, Food and Nature Initiative). 2015. *Landscape partnerships for sustainable development: achieving the SDGs through integrated landscape management*. https://peoplefoodandnature.org/publication/landscape-partnerships-for-sustainable-development

Mazzucato, M., Okonjo-Iweala, N., Rockström, J. & Shanmugaratnam, T. 2004. *The economics of water: Valuing the hydrological cycle as a global common good*. Colombo, Sri Lanka, Global Commission on the Economics of Water. https://economicsofwater.watercommission.org/report/economics-of-water.pdf

Meybeck, A., Cintori, L., Cavatassi, R., Gitz, V., Gordes, A., Albinelli, I., Opio, C. *et al.* 2024. Natural resources management for resilient inclusive rural transformation. *Global Food Security*, 42: 100794. https://doi.org/10.1016/j.gfs.2024.100794

Mottet, A., Bicksler, A., Lucantoni, D., De Rosa, F., Scherf, B., Scopel, E., López-Ridaura, S. *et al.* 2020. Assessing Transitions to Sustainable Agricultural and Food Systems: A Tool for Agroecology Performance Evaluation (TAPE). *Frontiers in Sustainable Food Systems*, 4: 579154. https://doi.org/10.3389/fsufs.2020.579154

Nilsson, M., Griggs, D. & Visbeck, M. 2016. Policy: Map the interactions between Sustainable Development Goals. *Nature*, 534(7607): 320–322. https://doi.org/10.1038/534320a

Orr, B.J., Cowie, A.L., Castillo Sanchez, V.M., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G. *et al.* 2017. *Scientific Conceptual Framework for Land Degradation Neutrality*. A Report of the Science-Policy Interface. Bonn, Germany, UNCCD. https://www.unccd.int/sites/default/files/documents/2019-06/LDN_CF_report_web-english.pdf

Simionesei, L., Ramos, T.B., Palma, J., Oliveira, A.R. & Neves, R. 2020. IrrigaSys: A web-based irrigation decision support system based on open-source data and technology. *Computers and Electronics in Agriculture*, 178: 105822. https://doi.org/10.1016/j.compag.2020.105822

Tittonell, P. 2023. *A Systems Approach to Agroecology*. Cham, Switzerland, Springer Nature. https://doi.org/10.1007/978-3-031-42939-2

United Nations. 2023a. *Summary of Proceedings of the United Nations Conference on the Midterm Comprehensive Review of the Implementation of the Objectives of the International Decade for Action "Water for Sustainable Development", 2018–2028*. New York, USA. https://www.un.org/pga/77/wp-content/uploads/sites/105/2023/05/PGA77-Summary-for-Water-Conference-2023.pdf

United Nations. 2023b. *Political declaration of the high-level political forum on sustainable development convened under the auspices of the General Assembly*. New York, USA. https://documents.un.org/doc/undoc/gen/n23/306/65/pdf/n2330665.pdf

UNCCD. 2019. *Decision 26/COP.14 Land tenure*. Bonn, Germany. https://www.unccd.int/sites/default/files/sessions/documents/2019-11/26-cop14.pdf

UNCCD. 2022. *Decision 27/COP.15 Follow-up on policy frameworks and thematic issues: Land tenure*. Bonn, Germany. https://www.unccd.int/sites/default/files/2022-10/27_cop15.pdf

UNCCD. 2023. *Integrated Land Use Planning and Integrated Landscape Management for Land Degradation Neutrality.* SPI Science-Policy Brief. Bonn, Germany. https://www.unccd.int/resources/brief/science-policy-brief-integrated-land-use-planning-and-integrated-landscape

UNEP. 2016. *Unlocking the sustainable potential of land resources: Evaluation systems, strategies and tools*. A Report of the Working Group on Land and Soils of the International Resource Panel. https://www.resourcepanel.org/reports/unlocking-sustainable-potential-land-resources#report

Verburg, P., Metternicht, G., Allen, C., Debonne, N., Akhtar-Schuster, M., Inácio da Cunha, M., Karim *et al.* 2019. *Creating an Enabling Environment for Land Degradation Neutrality and its potential contribution to enhancing wellbeing, livelihoods and the environment*. A Report of the Science-Policy Interface. Bonn, Germany, UNCCD. https://www.unccd.int/sites/default/files/2019-08/UNCCD_SPI_2019_Report_1.2.pdf

Ziadat, F., Berkat, O., Ouchna, R., Touami, M., Fetsi, T., Harari, N., Mekdaschi Studer, R. & Schlingloff, S. 2022. Participatory land resources planning to promote sustainable landscape management in rainfed areas-Morocco. *Frontiers in Sustainable Food Syst*ems, 6. https://doi.org/10.3389/fsufs.2022.848043

ANNEX

C3S (Copernicus Climate Change Service). 2023. Climate Data Store: Agrometeorological indicators from 1979 to present derived from reanalysis. Copernicus Climate Data Store (CDS). [Accessed on 13 February 2025]. https://doi.org/10.24381/cds.6c68c9bb

FAO. 1976. *A framework for land evaluation*. FAO Soils Bulletin, No. 32. Rome. https://www.fao.org/4/x5310e/x5310e00.htm

FAO. 2025. FAOSTAT: Crops and livestock products. [Accessed on 13 February 2025]. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

Fischer, G., Nachtergaele, F.O., van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D., & Tramberend, S. 2021. *Global Agro-Ecological Zones v4 – Model documentation*. https://doi.org/10.4060/cb4744en

IPCC. 2023. Sections. In: H. Lee & J. Romero, eds. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, pp. 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647

THE STATE OF
THE WORLD

2025
THE STATE OF THE WORLD'S LAND AND WATER RESOURCES FOR FOOD AND AGRICULTURE

THE POTENTIAL TO PRODUCE MORE AND BETTER

Land, soil and water resources are the foundations for agricultural production and global food security. Meeting the increasing demand for food will place additional pressure on resources that are already under severe strain: over 60 percent of human-induced land degradation occurs on agricultural lands (including cropland and pastureland), and agriculture accounts for more than 70 percent of global freshwater withdrawal.

The 2025 edition of *The State of the World's Land and Water Resources for Food and Agriculture* underscores the urgent challenges of human-induced land degradation, water scarcity, and climate change, and their impact on agricultural productivity and ecosystems; it examines the hidden and untapped potential of land and water resources to enhance sustainable agricultural production by safeguarding these finite resources.

While the report looks at land, soil and water in an integrated way, considering different production systems (crops, rangeland, forests, fisheries and aquaculture), particular attention is paid to crops drawing from a thorough analysis of main crop production potential based on data and information derived from the updated version of the Global Agro-Ecological Zoning (GAEZ) assessment. The report further explores sustainable solutions and integrated approaches for sustainable land, soil and water use and management, illustrated with examples, and identifies the key enablers required to scale them up for lasting and sustained impact.

The choices we make today for the management of land, soil and water will determine how we meet current and future demands while protecting the world's precious resources for generations to come.

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