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Science and Innovations for Food Systems Transformation

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Foreword

In December 2019, I received a letter from the United Nations Secretary-General requesting that I lead what he had just put together – the United Nations Secretary-General's Food System Summit 2021. My first thought at the request was that I did not need more work – I had enough on my plate. However, upon further deliberation, I could not help but consider the contradictory views on food and what it means to different people. By taking this role, I might have the opportunity to marshal a global consensus and provide the issue with momentum to generate actions for a clear way forward. I decided that I needed to attend the Summit to ensure that the issues that affect food systems from my part of the world be profiled globally, especially because, while Africa contributes 7% to global climate change, it is most exposed and its populations hit the worst due to poor resilience. I also wanted to ensure that I could bring out the engagement and voices of those most affected. Like the Secretary-General, I believe that the solutions to our challenges are already in our midst, simply needing to be profiled and harnessed for the benefit of all. Therefore, I was thrilled that, in the same letter, the Secretary-General had made it clear that the Summit was going to be anchored in science and that an independent group of the world's best scientific experts were being brought together.

The Scientific Group was thus set up as an independent group of experts under the leadership of Professor Joachim von Braun, a renowned and respected expert in science policy and a policy advisor to governments. A person with deep academic and scientific roots around the world, his work and views on zero hunger and what the world should be doing to come through on its promise by 2030 are very well know. The Vice Chairs of the Scientific Group, Profs. Kaosar Afsana from BRAC University (Bangladesh), Louise O. Fresco from Wageningen University (Netherlands) and Mohamed Hag Ali Hassan from Sudan (World Academy of Sciences), fostered scientific excellence and appropriate diversity in the Group as well.

The Scientific Group began work with a clear mandate: to draw on existing scientific research, collaborate with global science networks, advise the Summit and help the world understand food systems, specifically the status of things, what is at stake and how to go forward from where we are today. At the core of the Summit were the 2030 Agenda and how we get back on track. The Group was charged with ensuring that the Summit was anchored in science, drawing out the challenges of our food systems, and consolidating knowledge as to how to resolve these challenges. In a nutshell, the Scientific Group was to build consensus on the critical drivers for global food systems' transformation, including the priorities we need to implement between now and 2030 to get back on track.

The Scientific Group was composed of 28 experts from across scientific networks of institutions, designed to pull in global expertise and leading scientific views and to bring in views across all groups of society, from indigenous peoples, women, producers and so many more. It was also designed to draw in all of the food systems issues influencing and impacting our world, from people to our planet to the prosperity of both all around the world – all brought together in an intelligent and digestible way. Through rigorous work, open engagement and "Science Days", these experts engaged and consulted widely, and through meetings with other areas of the Summit. They kept abreast of key challenges that the world, societies and governments were concerned about, as informed by hundreds of dialogues, and were on top of the key emerging opportunities and possible practical game-changers through the work of Action Tracks and related peer reviews.

The UN Food Systems Summit Scientific Group dug deeply into their wide institutional networks of expertise, as per their TORS,[1] to bring forth the foremost scientific evidence. They looked at the progress that has been made so far and made recommendations on science-based approaches to achieving SDGs while revealing trade-offs associated with food system transformation. Through the networks of partners from all regions of the world, the Scientific Group brought diverse viewpoints, ensuring the inclusion of a diversity of frameworks and regional voices. The Group linked science-based synthesis to ongoing initiatives under the UN system, including the Committee on World Food Security (CFS) High-Level Panel of Experts, the CGIAR, science-based institutions and many other relevant knowledge institutions, to help advance future food systems.

This volume – a critical product of the Scientific Group – does a number of things, the most important of which is building a consensus on our understanding of food systems. This is particularly important given the breadth of the area under discussion, the diversity of views and interests, the number of other sectors that are impacted and the overall complexity of the food system globally.

The volume then goes on to identify science-driven innovations and opportunities that must be pursued in an integrated manner for a successful transformation of food systems. Here, the Group dwells on the key role of science and research as a prerequisite for innovations that will accelerate the transformation of current food systems to healthier, more sustainable, equitable and resilient systems. The volume also includes a number of chapters by partners of the Group that highlight the most critical areas, information and knowledge in different sectors and the gaps in

[1] The TORs can be found on the website of the Scientific Group here: https://sc-fss2021.org/about-us/tor-and-letters-un-leadership/

knowledge that still exist. The Scientific Group recommends actions that, if implemented, have the potential to transform our food systems. The chapters in this volume further emphasize the complexity of the food systems and a clear direction for the transformation of our food systems with a number of things that can be done together. Throughout this volume, it is clear that there is no one-size-fits-all: while the concepts are similar, the translation of science into policies that inform investments is only possible if placed within the specific context of where the work will be done in a country, in different parts of the world.

I am very proud of the work captured in this volume; most of all, I am grateful that the Scientific Group contributed to what I consider the most important outcome of the Summit – the fact that we have global censuses that our food systems must transform if we are to achieve the 2030 Agenda. Second, I am proud that the Scientific Group mobilized the global science community behind the Summit, from the least heard voices and the least referred-to science that sits with indigenous peoples to the most lucrative science behind big AG. All were brought forward and the opportunities and trade-offs evaluated, ensuring that everybody feels heard, but also that the most important aspects of how we go forward are clear.

As I conclude, I want to bring out the following areas that we must keep our eyes on as we move forward from the Summit to the Hub that will coordinate Summit follow-up and the UN agencies that will help the Hub to keep the world engaged – including tracking of the Summit's commitments. These are the need to: strengthen national capacities for implementation, especially in emerging economies, develop a clear financial agenda for investments needed to address increasing hunger, but also the overall 2030 Agenda; and better coordinate and advance institutional innovations that can improve the science, such as policy interfaces to enhance implementation in countries and better global level networked science services. Lastly, there is a need to facilitate stronger synergies of food system actions with other key areas, including climate policy, Covid-19-related policies, trade policies, conflict policies and related food price inflation that will exclude even more people from accessing the right level of nutrition and, at worst, leave them with no food at all.

The work and contribution of the Scientific Group of the Summit have provided incredible direction on how we move forward from here. There will always be need for new insights, and there will always be a need to sharpen the science/policy/action interface, but, for now I am incredibly grateful that through this volume the Scientific Group gives us the steering wheel that we need to move forward towards a food systems approach that could get us back on the 2030 Agenda, on food, health and diets, environment and the prosperity of people and the planet.

The UN Secretary-General's Special Envoy for the United Nations Food Systems Summit 2021
New York, NY, USA

Agnes M. Kalibata

The Approach of the UNFSS Scientific Group and an Overview of the Volume

The Scientific Group's Design and Approach

In April 2020, the Deputy Secretary-General of the United Nations invited Joachim von Braun to chair the Scientific Group for the UN Food Systems Summit. The mandate was as follows: "The Scientific Group is responsible for ensuring that the Summit brings to bear the foremost scientific evidence from around the world and helps expand the base of shared knowledge about experiences, approaches, and tools for driving sustainable food systems that will inform the future. The work of the Scientific Group ensures the robustness and independence of the science underpinning dialogue of food systems policy and investment decisions. It also informs the content of the Summit, its recommended outcomes, and the asks and commitments that emerge from the Summit."[2] It was new for a UN Food Summit to establish an independent Scientific Group with such a significant mandate.

The Scientific Group (ScGroup) constituted a team of 28 food systems scientists – social scientists, economists and scientists working within the natural and biological sciences, ecology and food technology – from all over the world, identified in consultation with research organizations.[3] They served in their personal capacities. ScGroup members developed a series of original scientific papers, which were peer-reviewed and scrutinized by governments, civil societies and members of the general public.[4] The inclusive approach of the ScGroup resulted in the earlier drafts of the chapters of this volume being widely distributed as inputs in preparation for the Summit. In addition, diverse viewpoints were sought from wide networks of partners of the ScGroup from all regions of the world.[5] These research partners were selected

[2] See https://sc-fss2021.org/wp-content/uploads/2020/11/Terms_of_Reference_web.pdf

[3] https://sc-fss2021.org/about-us/membership/

[4] https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/

[5] The Science Reader for the UNFSS: https://sc-fss2021.org/wp-content/uploads/2021/09/ScGroup_Reader_UNFSS2021.pdf

based on their commitment to scientific research and diversity of knowledge frameworks and regional coverage. They included academic and research institutions, policy think-tanks, UN agencies, academies of science, indigenous peoples' knowledge communities, private-sector research and advocacy organizations.[6] ScGroup members, along with other independent experts, served as commentators and reviewers of the contributions from the partners.

This volume compiles the findings of the ScGroup and its partners. The chapters have been further edited in the wake of the Summit. The chapters culminate the fulfillment of the ScGroup's mandate and provide science- and research-based, state-of-the-art, solution-oriented knowledge and evidence to inform the transformation of contemporary food systems in order to achieve more sustainable, equitable and resilient systems.

Volume Overview

This volume is divided into seven sections. While it is organized by key themes, the interdependence of food, health and environment systems is recognized, an interdependence vital for identifying innovations – technological, political, social and institutional – that can help to synergistically achieve multiple SDGs and end hunger by 2030.

Part I, on Food System Concepts and Summarized Recommendations, presents seven priorities for accelerating the transformation to healthier, more sustainable, equitable and resilient food systems. These are: (i) end hunger and improve diets; (ii) de-risk food systems; (iii) protect equality and rights; (iv) boost bioscience; (v) protect resources; (vi) sustain aquatic foods; and (vii) harness digital technology. This section also includes a key contribution by the ScGroup concerning sharpening food systems concepts and definitions so that these concepts are better understood when we make calls for food system transformation.

Part II deals with Actions on Hunger and Healthy Diets. The section begins with a definition of a healthy diet. It was an important, but not straight-forward, task to arrive at a widely accepted definition of healthy diets in the context of a world with many diverse food systems and cultures of dietary patterns. Also, concepts of sustainable and healthy diets were elaborated and remain themes under discussion. This section also focuses on zero hunger. Approaches for ensuring access to safe and nutritious food are explored, highlighting the need for a whole-system approach in policy and research, as well as monitoring and evaluating to manage externalities. The critical importance of comprehensive modeling of the synergies and trade-offs of policy actions is demonstrated. Solutions for enabling the shift to healthy and sustainable consumption are offered, including behavior change interventions, food education, improved product design, investments in food system innovations,

[6] https://sc-fss2021.org/community/partners/

regulatory regimes for food safety and more. Both the public and private sectors have important roles in responding to and shaping the market opportunities created by changing consumer demands. Attention is paid to the role of fruits and vegetables in healthy diets, and priorities for research and action are identified.

Part III delves into Actions for Equity and Resilience in Food Systems. This section discusses the various types of inequalities persistent within food systems and identifies key drivers of said inequalities. The increased inequalities at the national and also, recently, global levels are noted as major concerns for equitable food systems. Noting that the most effective way to sustainably eradicate poverty and inequality is to boost the opportunities and capacities of the poor and those living in situations of vulnerability, a wide range of actions are explored in the chapters to enhance inclusive decision-making, protect the livelihoods of those living in situations of vulnerability while creating opportunities and design policies and institutions to support equitable food system livelihoods. Opportunities for gender equality and women's empowerment are prominently discussed, as are opportunities for engagement and empowerment of youths. The future of small farms is prominently considered, and it is emphasized that food system transformation must serve smallholders and not leave them behind. Indigenous peoples' food systems received high attention from the ScGroup, and the enhanced cooperation between indigenous people's knowledge community and the scientific community is a real achievement of the UNFSS. The specific challenges faced by indigenous communities and their priorities for action are highlighted in a contribution in this section. Novel approaches to urban food systems' transformation in the emerging economies, including the role of secondary cities, are discussed. Foreign policy and security policy dimensions of food system failures are considered, because both the pathways to food insecurity from violent conflicts and those from armed conflicts to food crises have become much more prevalent in recent decades. The fundamental need to enhance food systems' resilience to vulnerabilities, shocks and stresses is addressed and different options for diversification are offered.

Part IV focuses on Actions for Sustainable Food Production and Resource Management. Chapters in this section explore the diversity of technological, institutional and policy innovations and actions for transforming the current "nature negative" food systems into ones that are "nature positive" in order to conserve, protect and regenerate natural resources and the natural environment, including biodiversity, through "nature positive" landscape-level interventions and agroecological practices. While important advances have been made in delineating pathways for agroecology to contribute to sustainable food systems, it is clear that much more research and dialogue is needed. The call for more research and dialogue also applies to issues of sustainable livestock production and animal-based foods. Relatedly, there is a growing understanding that food systems are not simply or only terrestrial systems and that efforts must be scaled up to embrace aquatic food systems so as to assure their sustainability and resilience as well. Climate resilience and climate mitigation were key topics that were widely accepted during the UNFSS process, and their key roles in food system transformation are addressed in various chapters. Similarly, the role of water, especially scarcity and water pollution, is tackled. It is recognized that the integration of biodiversity into agriculture and holistic approaches to plant nutrition that consider its hidden costs are integral to improving health, eliminating hunger and reducing negative environmental impact. The reduction of food loss and waste is confronted, and it is clear that action is needed for incentives and behavior change that will cut food waste and technologies that will cut food loss.

Part V discusses Costs, Investments, Finance and Trade Actions. This section begins with a chapter that advances our understanding of the true cost of food – reflecting the environmental and health-related costs of food. The emerging tragedy in the efforts around food system transformation is the extraordinarily high true cost of producing and processing food, estimated at about $30 trillion, compared to the relatively low cost of overcoming hunger, estimated at about $50 billion a year. An accompanying chapter assesses the cost and affordability of a basic meal around the world. Innovative financing solutions are offered to support the investments needed for achieving the SDG2 goals and ending hunger, and it is disappointing that they did not make it into the UNFSS action agenda. Similarly, important trade issues and trade policies that can complement countries' national policies for sustainable food systems are presented but were not taken up in the UNFSS action agenda.

Part VI shares Regional Perspectives. Chapters in this section show the great diversity in food systems around the world and indicate that follow-up actions for transforming food systems will need to be equally diverse. Chapters examine the opportunities for science, technologies, policies and innovations to transform food systems in Africa, Asia, Europe, Latin America and the Caribbean, as well as in large countries such as China, India and Russia. It is clear that there is much to learn, adapt and innovate from experiences within and across countries and regions, and there is an important opportunity for knowledge communities and networks to share experiences and insights in the follow-up to the UN Food Systems Summit.

Part VII concludes by addressing Strategic Perspectives and Governance. This section sets the stage for a broad review of the role of science, technology and innovation in transforming food systems around the world. The multidimensional concept of bioeconomy for the transformation of food systems is examined for its potentials and opportunities. Recognizing the extraordinary impacts of Covid-19, the links between global food security and "One Health" – the inter-connectedness of the health of people, animals, plants, soils, water and the environment – are discussed. It is widely acknowledged that science and policy will face challenges in regard to food system transformations at the global and national levels. Science-policy interfaces for transforming food systems emerged as a contentious topic during the UNFSS preparations – including what type of interface at what level – national or international – and whether existing interfaces are sufficient or new interfaces are needed. Another chapter details the key steps needed to transition and transform our food systems. The penultimate chapter of the section, and of this volume, reiterates the calls for exploring options for a global science-policy interface on food systems. It makes clear that the implementation of the Action Agenda of the UN Food Systems Summit and the transformation of food systems calls for enhancing countries' local science and research capacities. The final chapter of the volume presents three key opportunities for science to transform food systems: (i) strengthen research cooperation between scientific communities and indigenous peoples' knowledge communities, (ii) expand financing within governments to spend at least 1% of food system GDP on food system science, and (iii) establish pathways towards strong science-policy interfaces networked across national and international levels to enable evidence-based follow-ups to the action agendas established at the Summit.

The over-arching conclusion of this volume is that the global food system needs a revamp – in policies and institutions, as well as on the social, industrial and technological fronts.

Successes of the UN Food Systems Summit and Attention to Unfinished Business

It was a bold decision by the UN leadership to unleash a multi-stakeholder process, as well as invite an independent Scientific Group to mobilize science communities around the world to advise the Summit agenda with science-based evidence. The scientific and knowledge communities welcomed this move by the UN and have become energized to address complex food system problems with a renewed commitment to identify solutions.

The ScGroup considers the UN Food Systems Summit a success, but there is also unfinished business. When benchmarking against earlier summits, five promising outcomes are highlighted: (i) *political and societal engagement* – the Summit was much more inclusive and mobilized nations and stakeholders with multiple dialogue formats – never before has the world discussed and considered food system issues with attention to nutrition, health, ecology, and much more[7]; (ii) *scientific engagement* – also never before has science had the opportunity to contribute in so many ways to the agenda of a food summit – open debate and action orientation mobilized many adademies of science, research organizations, academics and practitioners; (iii) *action agenda* – the UN Secretary-General's statement of action, with its systems focus, and the five action areas to help inform the transitions needed to realize the vision of the 2030 agenda are noteworthy; (iv) *national level input and implementation* were appropriately emphasized; and (v) *significant global initiatives* on tackling hunger, healthy diets, anemia in women, agroecology, soil health, oceans and more were launched.

Yet, there are some important areas that require further attention in the future: (i) *strengthening the capacities* for implementation of actions at the national level, especially in emerging economies, is essential – this is an area for stakeholders to get together and catalyze the necessary actions, and scientific bodies can assist; (ii) *developing a strong finance agenda* for the investments needed to achieve the end of hunger and other key targets is important – the financial proposals, including

[7] See the Food Systems Summit Dialogues https://summitdialogues.org/

those from the ScGroup, did not find sufficient resonance, and other approaches are needed; (iii) encouraging institutional innovations and enhanced coordination for an *improved science – policy interface* at the global level that is well networked with regional and national interfaces remains critical; and (iv) facilitating strong global level actions in key areas such as *climate, Covid-19, and trade*, to accompany national level actions and implementation, is necessary, as is addressing emerging food price inflation.

This volume has been assembled to inform the way forward on the transformation of global food systems beyond the UN Food Systems Summit and to show how science can and must contribute to the transformation of food systems in order to end hunger and achieve the UN Sustainable Development Goals by 2030.

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Acknowledgements

We begin by expressing our appreciation to the United Nations Leadership for convening the Scientific Group for the United Nations Food Systems Summit, and thereby elevating the role of science in underpinning the dialogues, policies, and investment decisions that have emerged from the Summit. We are especially grateful to Deputy Secretary-General Amina Mohammed and to Special Envoy Agnes Kalibata and their excellent teams for their strong commitment to and continued encouragement and support for robust and independent scientific evidence and knowledge.

We warmly thank all the members of the Scientific Group for their extraordinary contributions in bringing the foremost scientific evidence from around the world. The Scientific Group constituted a team of 28 food systems scientists – social scientists, economists and scientists working within the natural and biological sciences, ecology and food technology – from all parts of the world. From July 2020 through December 2021, the Scientific Group held 14 meetings to plan, discuss and review its submissions to the Summit.[8] Members of the Scientific Group developed a series of original scientific papers, as well as undertaking peer reviews of papers contributed by partners, and they participated in *Science Days* and other important events in the lead-up to the Summit and during the Summit itself.[9]

We gratefully acknowledge the more than 40 global research partners who delivered science- and evidence-based, policy-focused research briefs covering a wide spectrum of food systems-related thematic areas, which are collected in this volume. These research partners included academic and research institutions, the CGIAR Centers, including the International Food Policy Research Institute (IFPRI), Indigenous Peoples' knowledge networks, policy think-tanks, UN agencies,

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[8]For the list of membership of the Scientific Group, see https://sc-fss2021.org/about-us/membership/. The minutes of all meetings are public, see: https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/

[9]For the list of papers by the partners of the Scientific Group, see https://sc-fss2021.org/wp-content/uploads/2021/07/FSS_ScG_Briefs_draft_list_20-7-2021.pdf

academies of science and private-sector research and advocacy organizations. Many of them also organized side events around *Science Days*, drawing attention to important emerging issues.[10]

The Scientific Group valued transparency, as well as peer review and peer culture. We thank Mahendra Dev, Zhu Jing, Per Pinstrup-Andersen, Pauline Scheelbeek and Moctar Toure for their peer reviews of the Scientific Group's own papers, and we thank the many other anonymous reviewers for their peer reviews of the partners' papers.

Science Days, held on July 8–9, 2021, was organized by the Scientific Group and facilitated and hosted by FAO with about 3,000 participants. Acknowledging the importance of concerns about inclusiveness, the Scientific Group has aimed at broad inclusiveness throughout, including at Science Days, to make sure all perspectives were heard. We are indebted to FAO Chief Scientist Ismahane Elouafi and her team, especially Preet Lidder and Florian Doerr for their excellent collaboration with this important event.[11]

Colleagues at the Center for Development Research (ZEF) at the University of Bonn provided exceptional support to the Scientific Group throughout its term, from administrative support to research support, communications support, website support and event organization support. We would like to particularly thank Heike Baumüller, Paula Rothenberger, Niklas Müller and Yesim Pacal. We thank Anja Köhler at ZEF for developing the great Scientific Group website https://sc-fss2021.org/ that served us all, and that will be maintained.

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Co-editors of the Volume and Former Chair and Vice Chairs of the Scientific Group for the UN Food Systems Summit

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Kaosar Afsana
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[10] See the authors and co-authors of these chapters at https://sc-fss2021.org/materials/fss-briefs-by-partners-of-scientific-group/ and the list of partners of the Scientific Group at https://sc-fss2021.org/community/partners/.

[11] For more on Science Days, see: https://sc-fss2021.org/events/sciencedays/

Contents

Part IV Actions for Sustainable Food Production and Resource Management

Water for Food Systems and Nutrition

Claudia Ringler, Mure Agbonlahor, Kaleab Baye, Jennie Barron, Mohsin Hafeez, Jan Lundqvist, J. V. Meenakshi, Lyla Mehta, Dawit Mekonnen, Franz Rojas-Ortuste, Aliya Tankibayeva, and Stefan Uhlenbrook

1 Introduction

Water is essential for all life and is integral to the function and productivity of the Earth's ecosystems, which depend on a complex cycle of continuous movement of water between the Earth and the atmosphere. Water is also fundamental for food systems, and a food systems transformation will be essential to meeting SDG 6 on water and sanitation. As described by the High-Level Panel of Experts on Food

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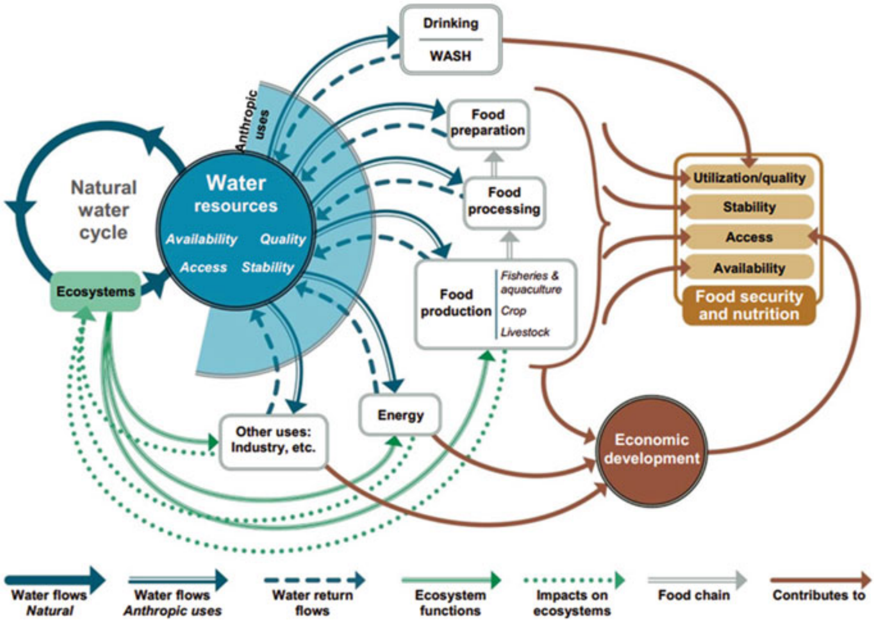

Fig. 1 The linkages between water and food systems (Source: HLPE 2015)

Security and Nutrition (HLPE) (HLPE 2015) and illustrated in Fig. 1, the key dimensions of water that are of importance for humanity are its availability, access, stability, and quality. These have multiple, close linkages and feedback loops with food systems, which can be defined as the activities involved in the production, processing, distribution, preparation, and consumption of food within wider socio-economic, political, and environmental contexts (HLPE 2017). For example, waste streams from food processing often re-enter water bodies, affecting other components of food systems, such as drinking water supplies (water is itself essential for all bodily functions and processes, and is an important source of nutrients) (UNSCN 2020), as well as water-based and water-related ecosystems.

More than 70% of all freshwater withdrawals are currently used for agriculture, and about 85% of withdrawn resources are consumed in irrigated agricultural production. With these resources, irrigated crop areas generate 40% of global food production on less than one-third of the globally harvested area (Ringler 2017). Another key water-food system linkage is water supply for WASH (water, sanitation

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and hygiene), which is important for human health, can support nutrition outcomes, particularly if combined with other interventions (Cumming et al. 2019), and is a basic human right, as is the right to food. Water is also essential for agricultural processing and food preparation.

Climate change and other environmental and societal changes (e.g., land use changes, biodiversity loss, urbanisation, and changing lifestyles and diets) are impacting the dynamics of natural water cycles and water resource availability, with further, subsequent impacts on food systems. More than half of all natural wetland areas have been lost due to human activity since 1900 and forest degradation affects streamflow regulation (Sun et al. 2017). At the same time, the growing frequency and severity of floods and droughts in many regions of the world (IPCC 2021) increase competition over water resources. This calls for changes in water management, including increased water productivity, integrated storage solutions, accelerated land restoration and smarter water distribution to support food systems, as well as a reduction in impacts on domestic, industrial, energy-related, and environmental water uses.

2 SDG 2 and SDG 6 Can Only Be Achieved If the Water and Food System Communities Work Together

2.1 Water Scarcity and Pollution Are Growing, Affecting Poorer Populations, Particularly Food Producers

Freshwater-related ecosystems include wetlands, rivers, aquifers, and lakes that sustain biodiversity and life (UN Environment 2018). Although they cover less than 1% of the Earth's surface, these habitats host approximately one-third of vertebrate species and 10% of all species (Stayer and Dudgeon 2010), including mammals, birds (IUCN 2019), and fish (Fricke et al. 2020). Water-related ecosystems are also vital for the function of all terrestrial ecosystems, providing regulating, provisioning, and cultural services (Martin-Ortega et al. 2015). Furthermore, hydropower is an essential energy source, accounting for 85% of global renewable electricity generation in 2015, but has since declined to around 60% (IEA 2016, 2020), and is also key for commerce and industry (Willet et al. 2019). Notably, de-carbonising the energy system can also adversely impact the water system, particularly in the case of increasing hydropower and biofuel production.

Progress on achieving the water and sanitation targets of SDG 6 has been unsatisfactory and uneven. More than 2 billion people live in places with high water stress (FAO SOFA 2020; UN 2018): by 2050, every second person, half of the world's grain production, and close to half of the globe's Gross Domestic Product might well be at risk from water insecurity (Ringler et al. 2016). In 2020, approximately 2.0 billion people lacked access to safely managed drinking water, and 3.6 billion people lacked access to safely managed sanitation services.

One in ten people lacked basic services, including the 122 million people who depend on untreated surface water, mostly in sub-Saharan Africa (UNICEF, WHO 2021). Poor women and girls, who are responsible for more than 70% of all water collection, spend about 200 million hours a day on this task, undermining their health and livelihood opportunities (UNICEF n.d.; Geere and Cortobius 2017).

In terms of agricultural water use, farmers across the world, but particularly in sub-Saharan Africa, continue to rely heavily on rainfall for food production. More than 62 million hectares of crop and pastureland experience high to very high water stress and drought, affecting about 300 million farm households (FAO 2020). With climate change, temperatures and crop evaporation levels are increasing, and there is growing uncertainty about the timing, duration and quantity of rainfall, increasing the risks related to producing food and undermining the livelihood security of the majority of rural people (AUC 2020). Fertiliser use on crop land and livestock excreta are key sources of agricultural water pollution, affecting aquatic life and threatening human health. Projections suggest that nitrogen and phosphorous deposition in water bodies will grow rapidly, particularly in low- and middle-income countries (Xie and Ringler 2017).

With respect to the other SDG 6 targets, such as water use efficiency, water-dependent ecosystems, and integrated water management, progress has been slow and is often not well understood, due to the lack of effective monitoring mechanisms and insufficient data. New, integrated approaches and reinforced efforts to measure and manage water are urgently needed (Sadoff et al. 2020).

While water availability differs dramatically around the globe, differences in access are most often due to politics, public policy, lack of capacity and investment, and flawed water management strategies, as well as exclusions due to geography (i.e., remote rural areas), gender, ethnicity, caste, race, and class. In many cases, water does 'flow uphill' to power and money (Mehta et al. 2019). Furthermore, increasing urbanisation and changing diets are affecting the demand and supply of water resources for food systems and aggravating water stress in many parts of the world, particularly in water-scarce areas of low/middle-income countries where coping capacity is often insufficient.

2.2 *Malnutrition Levels Are on the Rise and Are Closely Linked to Water Scarcity*

An estimated 690 million people, or 8.9% of the global population, were undernourished in 2019, prior to the COVID-19 pandemic (Headey et al. 2020). The number has since grown to between 720 and 811 million people (2020 values). Moreover, 149 million children below the age of five were stunted, 45 million were wasted, and another 39 million were overweight (FAO, IFAD, UNICEF, WFP and WHO 2021). Climate change, associated conflict, and a lack of sufficient water for food production, including irrigation for fruit and vegetable production, are key contributors to unaffordable diets and overall levels of undernutrition. At the same time, overweight continues to dramatically increase around the globe, including in children. Latin America, in particular, suffers from the associated public health burden. Overall, rural areas are currently experiencing the most rapid rate of increase in overweight (NCD Risk Factor Collaboration et al. 2019). Given these trends, neither the 2025 World Health Assembly nutrition targets nor the 2030 SDG nutrition targets will be met. As with inequities in access to water, inequities in access to food and nutrition are highest in rural areas (Perez-Escamilla et al. 2018).

2.3 SDG 2 and SDG 6 Targets Are Co-Dependent

Ending hunger and malnutrition requires access to safe drinking water (SDG 6.1), as well as equitable sanitation and hygiene (SDG 6.2). The underlying productivity (SDG 2.3) and sustainability (SDG 2.4) of agricultural systems are also dependent on adequate availability (SDG 6.4 and 6.6) of good quality (SDG 6.3) water. Moreover, water and related ecosystems (e.g., wetlands, river or lakes in SDG 6.6), which are embedded in sustainable landscapes, are important contributors to sustainable agriculture through regulating and providing water for food production (SDG 2.4) (Ringler et al. 2018).

A key contributor to poor nutritional outcomes in subsistence farming households in low-income countries is the seasonality of production, leading to a seasonality in diets, which can affect pregnancy outcomes and child growth (Baye and Hirvonen 2020; Madan et al. 2018). Well-managed irrigation systems can buffer seasonal gaps in diets, contributing to improved food security and nutritional outcomes, for example, through homestead gardening (Baye et al. n.d.; Hirvonen and Headey 2018).

It is equally important to stress the need for changes in food systems in meeting SDG 6 targets: reducing food loss and waste in food value chains (SDG 12.3), lowering pollution from slaughterhouses, food processing, and food preparation, and considering environmental sustainability in food-based dietary guidelines. All of these actions will be essential to meet the SDG 6 targets (UNSCN 2020).

3 Solutions for Improving Food System Outcomes and Water Security

Based on the above assessment, as well as recent water-food system reviews (Ringler et al. 2018; UNSCN 2020; Mehta et al. 2019; Young et al. 2021), the following actions are proposed for uptake by governments, the private sector, and civil society.

3.1 Strengthen Efforts to Retain Water-Based Ecosystems and Their Functions

The ecological processes underlying the movement, storage, and transformation of water are under severe threat from deforestation, erosion, and pollution, with impacts on local, regional, and global water cycles (WWAP 2018). In addition to a direct halt of deforestation and the destruction of water-based ecosystems, nature-based solutions that use or mimic natural processes to enhance water availability (e.g., groundwater recharge), improve water quality (e.g., riparian buffer strips, wetlands), and reduce risks associated with water-related disasters and climate change (e.g., floodplain restoration, wetlands) should be strengthened (WWAP 2018). Limiting overconsumption of water, particularly in water-stressed regions, will be necessary to stay within sustainable water use limits (Yu et al. 2021).

3.2 Improve Agricultural Water Management for Better Diets for All

Around 3 billion people on this planet cannot afford a healthy diet, particularly dairy, fruits, vegetables, and protein-rich foods (FAO, IFAD, UNICEF, WFP, WHO 2021). Both rainfed and irrigated systems play essential roles in lowering the prices of nutrient-dense foods, growing incomes to be able to afford these foods, and strengthening the diversity of foods available in local markets (Hirvonen et al. 2017).

3.2.1 Strengthen the Climate Resilience of Rainfed Food Systems

Rainfed systems produce the bulk of food, fodder, and fibre, and most animal feed is produced under rainfed conditions (Heinke et al. 2020). These systems are under severe and growing stress from climate change, including extreme weather (FAO 2020). This can be addressed, to some extent, through structural measures (e.g., terracing, soil bunds, drainage), investment in breeding, improved agronomic practices, effective incentives (e.g., payments for watershed conservation), and strong institutions for water, soil and land management (e.g., watershed committees) (Jägermeyr et al. 2016; World Bank 2010).

3.2.2 Strengthen the Nutrient Density of Irrigated Agriculture

As irrigation accounts for the largest share of freshwater withdrawals by humans (more than 90% in some agrarian economies), the potential for water conservation is also largest in this sector. Irrigation development needs keep environmental limits – which are increasingly affected by climate change – in mind. This includes addressing groundwater depletion. The potential for increasing water and nutrition productivity in irrigation remains large. It includes crop breeding for transpiration efficiency, salinity tolerance, climate resilience and increased micronutrients, integrated storage solutions – such as joint use of grey and green infrastructure – advanced irrigation technology, and soil moisture monitoring (Rosegrant et al. 2009). There are clear trade-offs between the nutrient density of foods and irrigation water use. Fruit and vegetable yields depend on frequent water applications in many parts of the world (although the water content of the end product also tends to be high) and need precision applications of agrochemicals to maximise water inputs and avoid water pollution (Meenakshi and Webb 2019). Many livestock products are highly water-intensive due to animal feeds, although the majority of the feed comes from rainfed agriculture. Awareness-raising and social learning interventions can help internalise the water externality of water-intensive diets. Improved coordination of water with other agricultural inputs can also enhance yield per drop of water. This requires access to technology packages, as well as to better agricultural information (Lundqvist et al. 2021), which is increasingly supported by ICTs (Asenso-Okyere and Mekonnen 2012). Moreover, subsidies for water-intensive crops, such as rice, milk and sugar, should be revisited and eventually removed. For water-scarce countries, importing virtual water via food and other commodities will remain essential (Allan 1997).

3.2.3 Address Water Pollution to Improve Food Production, Food Safety, and Water-Based Ecosystems

Globally, 80% of municipal sewage and industrial wastewater with heavy metals, solvents, toxic sludge, pharmaceuticals, and other waste are directly discharged into water bodies, affecting the safety of food, particularly vegetable production, and also, directly, human health (WWAP 2018). Agriculture also directly pollutes aquatic ecosystems and risks food production with pesticides, organic matter, fertilisers, sediments, pathogens, and saline drainage (UNEP 2016). Key measures to address agricultural and overall water pollution include the breeding of crops with higher crop nutrient use efficiency, better agronomic practices, the expansion of nature-based solutions for pollution management, low-cost pollution monitoring systems, improved incentive structures for pollution abatement, and continued investment and innovation in wastewater treatment, including approaches such as implementing the 3Rs (reduce, reuse, and recycle) of the circular economy across the entire food system (Mateo-Sagasta et al. 2018).

3.3 Reduce Water and Food Losses Beyond the Farmgate

Irrigated agriculture is often focused on high-value crops with a higher share of marketed surplus, compared to rainfed agriculture (Nkonya et al. 2011). At the same time, many irrigated crops, such as fruits and vegetables, are time-sensitive, perishable products that require efficient market linkages to consumption centres. Strengthening market linkages includes investment in physical infrastructure that supports on-farm production (irrigation, energy, transportation, pre- and post-harvest storage), efficient trading and exchange (telecommunications, covered markets), value addition (agro-processing and packaging facilities), and improved transportation and bulk storage (Warner et al. 2008). Investments are also needed in ICTs that facilitate farmers' access to localised and tailored information about weather, water consumption, diseases, yield, and input and output prices (Elsabber 2020).

3.4 Coordinate Water with Nutrition and Health Interventions

3.4.1 Strengthen Institutional Coordination and Develop Joint Programmes

Governance and management of water for various uses and functions, as shown in Fig. 1, follow different institutional arrangements. Similarly, professionals engaged in various roles within water-related institutions have different kinds of training and experiences. Few irrigation engineers have a professional background or skills related to WASH, and few WASH professionals have the technical skills needed to design water infrastructure for multiple uses, for example. The notion of integrated water resource management (SDG 6.5) has been promoted as a principle to overcome problems due to sectoral division. Coordination at the lowest appropriate levels is urgently needed between WASH and irrigation for improved food security, nutrition, and health outcomes, as well as to strengthen women's agency over water decisions. Multiple-use water systems can increase food security and WASH outcomes (van Koppen et al. 2014). An example is the MiAgua programme in Bolivia supported by CAF, the development bank of Latin America, which included rural water supply, climate change adaptation measures such as watershed protection, and micro-irrigation projects for small-scale agriculture. MiAgua benefited 2.25 million people with improved or new access to water and contributed to increasing rural water coverage from 59 percent in 2011 to 69% in 2020. At a larger scale, improved coordination across riparian countries is essential for improving water securities linked to competing uses. A key example is the Aral Sea Basin, where lack of coordination between upstream and downstream countries affect both energy and food security (Bekchanov et al. 2015).

3.4.2 Implement Nutrition-Sensitive Agricultural Water Management

Nutrition and health experts need to join forces with water managers at the farm household level, at the community level, and at the government level to strengthen positive transmission pathways between both rainfed and irrigated agriculture and food and nutrition security. A recent guidance (Bryan et al. 2019) describes eight actions for increasing the nutrition sensitivity of water resource management and irrigation, as well as indicators for monitoring progress.

3.5 Increase the Environmental Sustainability of Food Systems

The water footprint of diets varies dramatically between rich and poor countries, but also by socioeconomic group within countries (Lundqvist et al. 2021). More work is urgently needed on the impact of current dietary trends on environmental resources, including water. Food-based dietary guidelines should consider the environmental footprint of proposed diets, whereby government regulations and consumer awareness should be strengthened to reduce the over-consumption of food, and further efforts are needed to reduce post-harvest waste and losses (UNSCN 2020).

3.6 Explicitly Address Social Inequities in Water-Nutrition Linkages

Vulnerable groups need to be proactively included in the development of water services, including incorporating their needs and constraints into initial infrastructure design. For rural smallholders who most lack water and food security, irrigation design should consider multiple uses of water, such as drinking, irrigation, and livestock watering, to meet women's and men's needs. While women make up a large part of the agricultural workforce, they often lack recognition and formal rights, and farmers are often considered to be 'male' in many parts of the world. Women's productive roles should be promoted, and they should be trained in irrigation and water management. Their involvement has important implications for water and food security (Meinzen-Dick et al. 2021; Balasubramanya 2019). It is also important to ensure that women and disadvantaged social groups (e.g., lower castes, stigmatised social groups) have equal access to credit, irrigable land, labour, and markets to be able to buy agricultural inputs and sell their produce (Mehta et al. 2019; UNSCN 2020).

3.7 Improve Data Quality and Monitoring for Water-Food System Linkages, Drawing on Innovations in ICT

Better data are needed if we are to truly understand the water footprint of diets and devise policies that co-maximise water and food security and nutrition goals. Challenges include poor water and poor food intake data and a lack of indicators connecting the two, but improvements are emerging (Bryan et al. 2019; HWISE network (https://hwise-rcn.org/); Lundqvist et al. 2021). More and better data will support better water management and food systems and increase transparency in decision-making. This requires sustained investments in the monitoring of a wide range of hydrological and food-related parameters worldwide. Modern Earth observation methods can support larger-scale assessment, but need to be complemented by dedicated field measurements.

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