the interacademy partnership

Opportunities for future research and innovation on food and nutrition security and agriculture

The InterAcademy Partnership's global perspective

Synthesis by IAP based on four regional academy network studies

ISBN: 978-88-940784-5-9

This report can be found at
www.interacademies.org

Network of African Science Academies NASAC

The Association of Academies and Societies of Sciences in Asia (AASSA)

IANAS Interamerican Network of Academies of Sciences

European Academies Science Advisory Council (EASAC)

Opportunities for future research and innovation on food and nutrition security and agriculture

The InterAcademy Partnership's global perspective

Synthesis by IAP based on the four regional academy network studies

ISBN 978-88-940784-5-9

InterAcademy Partnership
ICTP Campus, c/o TWAS
Strada Costiera 11
34151 Trieste
Italy

InterAcademy Partnership
US National Academies of Science,
Engineering, and Medicine
500 Fifth St. NW
Washington, DC 20001
USA

www.interacademies.org
iap@twas.org
secretariat@iapartnership.org

Cover images. Top left: mass soybean harvesting at a farm in Campo Verde, Mato Grosso, Brazil; © Shutterstock. Top right: copyright istock by Getty Images. Bottom left: copyright Shutterstock. Bottom right: copyright Professor Sheryl Hendriks.

Copy-edited and typeset in Frutiger by The Clyvedon Press Ltd, Cardiff, United Kingdom

Printed by Schaefer Druck und Verlag GmbH, Teutschenthal, Germany, on FSC-certified paper

Contents

		page
Foreword by IAP President		**v**
Summary		**1**
1	**Scope and scale of the scientific opportunities**	**5**
1.1	Introduction	5
1.2	Global challenges for FNSA	6
1.3	Science and technology advances can strengthen the evidence base	7
1.4	Design of the IAP project and this report	9
1.5	What steps have already been taken to address the challenges of improving global FNS?	10
1.6	IAP's intended audiences	10
2	**Assessing regional diversity and commonalities**	**11**
2.1	IAP starting point: key themes for FNS mapped onto the SDGs	11
2.2	Variation within and between the regions	11
2.3	Characterising diversity in FNSA	12
2.4	Variability in scientific infrastructure and research capabilities	13
2.5	Variability in linkage of research outputs with development of policy options	14
2.6	Consensus between the regions and policy implications	15
2.7	From regional analysis to global priorities	16
3	**Efficient and equitable food systems: defining the challenges, and the opportunities for innovation**	**19**
3.1	Scope and efficiency of food systems	19
3.2	Circular and bioeconomy	20
3.3	Climate change	21
3.4	Food waste and recycling	22
3.5	Food processing	23
3.6	Understanding global markets and addressing their volatility	23
3.7	Connections with basic science, digitisation and big data	24
4	**Transforming diets for nutrition outcomes and public health**	**27**
4.1	Issues related to malnutrition and defining healthy and sustainable diets	27
4.2	Overweight and obesity	29
4.3	Variation in population sub-groups	30
4.4	Exploring health co-benefits of climate change mitigation by changing diet	30
4.5	Food structure and content	31
4.6	Food safety	32
4.7	Innovation in nutrition and capitalising on work at the scientific frontiers	33
4.8	Nutrition-sensitive systems	34
5	**Agricultural productivity and its transformation amidst uncertainty**	**37**
5.1	Farming structures	37
5.2	The challenge of climate change for agriculture	38
5.3	Agricultural productivity and the needs of end users	39
6	**Competition for natural resources: sustainable development and the wider ecosystem**	**45**
6.1	Water	46
6.2	Soil	47
6.3	Energy use and generation	48
6.4	Biodiversity	48

7 Enhancing R&D and science advice **51**
7.1 Issues for building research infrastructure, collaboration and effective translation 51
7.2 Policy issue integration and reform 53
7.3 Roles of academies 53
7.4 International scientific advisory groups for FNS 54

8 Recommendations **57**

Appendix 1 Preparation of the IAP global report **61**

Appendix 2 Characteristics of the current global status of FNS analysis—and the research implications **63**

Appendix 3 IAP template **65**

Appendix 4 Collated list of recommendations from all four regional reports **69**

Abbreviations **81**

References **83**

Foreword

The InterAcademy Partnership (IAP), the global network of the world's science academies, brings together established regional networks of science and medical academies, enabling the voice of science to be heard in addressing societal priorities.

All countries face the problem of tackling the burden of malnutrition as part of their efforts to achieve the United Nations Sustainable Development Goals. The most recent annual review by the Food and Agriculture Organization of the United Nations (FAO), in 2018, notes that the absolute number of undernourished people has continued to increase, between 2016 and 2017, and expresses concern that other nutrition targets are also being missed. Climate extremes and variability are threatening to erode and reverse previous gains made[1].

To address these global challenges, there is an urgent need to build critical mass in research and innovation, and to mobilise those resources in advising policymakers and others. In our IAP project on "Food and Nutrition Security and Agriculture" (FNSA), described in this report, we aim to show how academies of science can contribute to sharing and implementing good practice in identifying and elucidating controversial issues, to developing and communicating the evidence base, and to informing and monitoring the choice of policy options. Notably, with regard to one of the topics reviewed in this report, it is becoming clearer that climate change will have negative impacts on food systems in various ways, necessitating the introduction of climate-smart agriculture, but also that agriculture itself contributes substantially to climate change. Mitigating this contribution depends on introducing climate-smart food systems with efforts to influence consumer behaviours associated with excessive greenhouse gas emissions: changing dietary consumption could bring co-benefits to health and climate. Climate change issues are relevant to many of the Sustainable Development Goals, and agriculture and food systems are vital vehicles for achieving them. However, collectively, there is need to be more ambitious in identifying the scientific opportunities for systems in transition in an uncertain and rapidly connected world.

For the IAP project, working groups from four parallel regional academy networks were constituted: in Africa (the Network of African Science Academies, NASAC), Asia (the Association of Academies and Societies of Sciences in Asia, AASSA), the Americas (the Inter-American Network of Academies of Science, IANAS) and Europe (the European Academies' Science Advisory Council, EASAC). The project procedures were as follows. After agreement from all IAP academies on the overall scientific scope and project design, a meeting of the academies' experts on food and nutrition security and agriculture from the four global regions was arranged. The result was 10 guiding priority questions, the responses to which from each region would constitute the foundation of the academies' analysis. Over the course of approximately one year, the four regional working groups developed their advice. They consulted additional sources of evidence, including at national level, according to regionally agreed priorities. Occasional plenary global meetings brought together all regions, together with representatives from policy-making bodies. The outputs from the regional work were then subject to academy-nominated independent peer review, and the final texts were endorsed by the responsible academy networks. Publication of the regional reports in Africa, Asia, the Americas and Europe was accompanied by engagement with the science and policy communities in those regions and at national level. The feedback to the four regional reports was also used as a resource to prepare this fifth, global report under the auspices of an expert editorial group, accompanied by continuing interaction between the regions. The global report was independently peer reviewed and endorsed by IAP.

The four regional reports are published on http://www.interacademies.org/37646/Food-and-Nutrition-Security-and-Agriculture and the present report is the fifth, representing the global analysis and synthesis of our work. The purpose of this report is to advise on inter-regional matters, local–global connectivities, and those issues at the science-policy interfaces that should be considered by inter-governmental institutions and other bodies with international roles and responsibilities.

We are aware, of course, that there are many other reports available on the range of issues that IAP covers. Our efforts are designed to add value to the large body of work already undertaken by many other groups. We consider that the power of the IAP contribution is determined by the innovative and distinctive nature of the project in various respects:

- The IAP initiative represents a global cooperative network with the combined resources of 130 academies of science and medicine.
- The project design is inclusive, in being based on regional expertise across multiple scientific

[1] FAO, IFAD, UNICEF, WFP and WHO (2018). The state of food security and nutrition in the world. http://www.fao.org/3/I9553EN/i9553en.pdf.

disciplines, concomitantly recognising the core importance of basic research. Regional problems were addressed and the findings integrated to provide conclusions linking national–regional–global perspectives.

- The scientific analysis and advice are evidence-based and independent of commercial or political bias. IAP is open and transparent in processes.
- The project takes a food systems approach to encompass all of the steps involved from growing through to processing, trading, purchasing, consuming and disposing of, or recycling, waste.
- The agreed starting point emphasised that setting priorities for increasing agricultural production through sustainable intensification must take account of pressures on other critical natural resources, particularly water, soil and energy, and the continuing need to avoid further loss in ecosystem biodiversity.
- This fifth report demonstrates strong consensus around controversial issues, while acknowledging diversities in agriculture, food and nutrition systems, and in political systems.

The IAP regional and global reports form a basis for the academies' commitment to continuing engagement in broadening discussion, testing recommendations, and informing policy and practice, with particular regard to (1) acting on the available scientific knowledge and data to support responsible innovation, improve robust and coherent strategy development and shape public understanding of the challenges; and (2) building global scientific capacity and partnerships to identify new research priorities and close knowledge gaps[2].

The present report documents various examples of the opportunities for technological, regulatory and societal innovation. I take the opportunity here to emphasise that it is important to appreciate the necessary linkages between these different forms of innovation. For example, very recently the annotated reference genome for wheat has been published[3], which represents a community resource to drive wheat improvement by genomics-assisted breeding. However, regulatory systems around the world must be sufficiently flexible to enable and encourage innovation arising from the increasing pace of scientific discovery. That this may not always be the case is illustrated by the recent decision of the European Court of Justice[4] on new plant breeding techniques. It is important that regulatory frameworks are evidence-based and proportionate.

Our IAP reports provide an extensive resource in terms of evidence compiled, expert analysis shared and science-based recommendations proffered. We see that there is urgent need for political action to address the issues highlighted and put into place the means to transform food and nutrition systems to deliver sustainable, healthy diets. Academies and their networks remain very committed to using these findings to engage further with the wider science community, policymakers and other stakeholders. Recently, the regional outputs were communicated to a meeting organised by the S20 academies as part of the G20 discussions hosted by Argentina, the current G20 President[5], and we are now working actively to catalyse other discussion and action. We welcome feedback on the issues covered in this report and how, collectively, we can pursue new directions.

I thank the many scientific experts who have generously contributed their time, expertise and enthusiasm to our regional working groups and our global editorial group. I also thank all of our peer reviewers for their commitment and all of our academies and their regional networks, my IAP Board colleagues, and our core project secretariat for their sustained efforts. All of us in the IAP project also express our thanks for the very significant financial support provided by the German Federal Ministry of Education and Research (BMBF).

Volker ter Meulen
President of IAP
October 2018

[2] For example, since completion of our IAP work, a report from the US National Academies of Science, Engineering and Medicine clarifies research opportunities: "Science breakthroughs to advance food and agricultural research by 2030", July 2018.
[3] International Wheat Genome Sequencing Consortium (2018). Shifting the limits in wheat research and breeding using a fully annotated reference genome. *Science* **361**, eaar7191.
[4] European Court of Justice 25 July 2018, Judgement in Case C-528/16, on https://curia.europa.eu/jcms/upload/docs/application/pdf/2018-07/cp180111en.pdf.
[5] http://www.s20argentina.org/documents/

Summary

All countries face the problem of combatting malnutrition in its various forms: undernutrition and micronutrient deficiencies as well as overweight and obesity. The scale and nature of these problems of course differ across countries and their populations. Latest data from the United Nations indicate worrying trends in global food and nutrition security that must be tackled. Science has the potential to find sustainable solutions for national and global food systems relating to the complex interplay of issues spanning health, nutrition, agriculture, climate change, ecology and human behaviour.

Project design and purpose

With this report, global academies of sciences are expressing their concern about adverse tendencies in food, nutrition and agriculture, and identify science-based initiatives that could contribute to solutions. Academies of science have a substantial history of interest and achievement in these areas. The academies also took note of important other food and agriculture strategy and assessment papers (summarised in Appendix 2). The present work by the InterAcademy Partnership (IAP), the global network of science academies, brings together established regional networks of academies, forming a new collaboration to ensure that the voice of science is heard in addressing societal priorities. The added value aimed for with this academies' programme is to bring the science power of academies to focus on the protracted food, nutrition and agriculture issues. This seems increasingly called for as basic science – well represented in academies – becomes more and more relevant and integrated with applied problem-solving science in nutrition, food and agriculture. Another contribution is the emphasis on food systems and in that context a significant emphasis on health of people and the environment.

The first phase of the IAP project on 'Food and Nutrition Security and Agriculture' (FNSA) was designed to comprise four parallel regional academy network working groups (in Africa, Asia, the Americas and Europe), each consisting of experts from across the region, drawing on excellent science, and proceeding from a common starting point represented by an agreed IAP template of principal themes. Reports from these four regional groups were published in late 2017 and early 2018. In the second phase of the IAP project reported here, the focus is on the global level. Outputs from the four regional assessments, together with global analyses, were used as resources to generate this present, fifth report.

Framing

Our global focus derives from three key perspectives:

(i) Science to strengthen and safeguard international public goods, i.e. those goods and services that have to be provided on a scale that is beyond countries and can be achieved better collectively, and we emphasise the generation and use of key elements of science and its exchange as an international public good.

(ii) International environmental and institutional risks and their transmission in an uncertain and rapidly connected world, as well as opportunities and risks of innovations and technologies, again, from a science perspective.

(iii) The United Nations Sustainable Development Goals, which provide a critically important policy framework for understanding and meeting the challenges. However, they require fresh engagement by science to resolve the complexities of evidence-based policies and programmes, as well as resolving potential conflicts among goals.

We define the desired outcome for food and nutrition security as access for all to a healthy and affordable diet that is environmentally sustainable and culturally acceptable. The major global challenges for delivering food and nutrition security are compounded by the pressures of a growing population, urbanisation, climate change and other environmental change, economic inequality and market instability, as well as political disruptions and social injustices.

A coherent strategy to tackle the challenges must encompass both supply-side and demand-side elements. We take the integrative food systems approach to include all the steps involved in the food value chain, from growing and agronomics to processing, transporting, trading, purchasing and consuming. We examine issues for resource efficiency, environmental sustainability, resilience and the public health agenda, while also taking account of the local–global interconnectedness of systems.

In considering the triple burden of malnutrition (undernutrition, micronutrient deficiencies, and overweight and obesity), we explore a wide range of scientific opportunities. We evaluate how the current scientific evidence base can shape public understanding of the challenges, serve as a resource for innovation and inform policy options, and what the research agenda should be to fill current knowledge gaps. Capitalising on scientific opportunities is something that should pervade public policy widely; it is not just a matter for those funding and prioritising the research agenda and it should involve all of the stakeholders along the value chain.

Broad recommendations

1. We highlight throughout this report the importance of internationally supporting and sharing basic and applied research for improved food, nutrition and agriculture. Specifically, the report calls for more coordinated action on priority themes of international relevance among different research funders.

2. Translation of research to innovation requires stronger connections across disciplines and with cutting-edge technologies, linkage to science education, training and outreach. Social science and policy research on food, nutrition and agriculture on the one hand is challenged to enter in deep cooperation with life sciences and basic research on the other, and vice versa.

3. Upgrading scientific infrastructure is vital, as is sustained funding support for research, but it is also important to engender more collaboration between countries, to share scientific expertise and facilities and help build capacity in emerging economies. New trans-regional research efforts are warranted, accompanied by commitment to trans-regional engagement between the scientific and policy communities on the Sustainable Development Goals, climate objectives and cognate matters.

Recommendations for international scientific priorities

1. *Developing sustainable food and nutrition systems, taking a systems perspective to deliver health and well-being, linked to transformation towards the circular economy and bioeconomy.* The research agenda includes understanding drivers of efficiency and risk worldwide; clarifying issues for fair and rules-based trade and equitable and resilient markets; exploring emerging post-harvesting opportunities in food science, technology and engineering, for example for food safety and food processing and reduction of food losses and waste.

2. *Emphasising transformation to a healthy diet and good nutrition.* How is it constituted? How is it measured? How is it delivered? The research agenda includes exploring how to influence consumer behavioural change and private sector actions for healthy food choices; assessing implications for diet and nutrition across the life span; understanding health co-benefits of climate change mitigation; studying mechanisms for the associations between diet-gut microbiome-disease.

3. *Understanding food production and utilisation issues, covering considerations of efficiency, sustainability, climate risks and diversity of resources.* The research agenda for primary production includes evaluating impacts of climate change on food systems and natural resources; assessing new farming structures and technologies; characterising options for neglected and new food and feed sources, and for food from the oceans/aquaculture and for diversified food systems in response to regional and cultural differences.

4. *Capitalising on opportunities coming within range in the biosciences and other rapidly advancing sciences.* Choices should be made at the national and regional levels but on the basis of global sharing of evidence. The research agenda includes improving crop protection from abiotic and biotic stress; promoting animal health and feed conversion efficiency; clarifying how technology can augment precision agriculture for example using sensors to collect and monitor agronomic information.

5. *Addressing the food–energy–nutrients–water–health nexus, recognising that boundaries are blurred.* The research agenda includes developing scenarios for balancing objectives and improving ability to analyse risk and opportunity in trade-offs between different ecosystem services, such as related to water and land use systems; assessing critical competition, bioeconomy and circular economy issues for food–energy interdependencies; improving the evidence base for cost-effective soil management and for assessment of transboundary air pollution and diseases.

6. *Promoting activity at the science–policy interfaces and reconciling policy disconnects.* Addressing the scientific themes in the priorities listed in preceding items will help to inform a wide range of policy actions and, in turn, requires policy support to facilitate scientific endeavour. Research policy support in international food, nutrition, and agriculture is needed across multiple dimensions, for example to reform international trade frameworks to avoid trade conflicts, generate robust but flexible and proportionate regulation of emerging technologies, agree international standards in food safety and to coordinate initiatives for the circular economy and bioeconomy. It is also vital that the scientific community engages with the users of research and the public-at-large, including involving them in strategic decisions about planning research.

7. *Consolidating and coordinating international science advisory mechanisms.* The work required to initiate and maintain a coherent policy framework necessitates attention be given to constituting an International Panel for Food and Nutrition Security

and Agriculture, thereby serving to strengthen science strategies and support for research in these fields of vital importance for the world population and support international governance mechanisms and policy with evidence.

Actions to be taken by academies

IAP encourages and supports its academies and their regional networks in progressing the priorities listed in the preceding items. In these regards, key academy responsibilities should include the following:

(i) International advisory roles – supporting existing strategic collaborations such as G7 and G20 and participating in the proposed International Panel on Food and Nutrition Security and Agriculture.

(ii) Academy science policy advisory capacity-development – by sharing knowledge and expertise within the regional academy networks.

(iii) Monitoring progress in science and innovation – at national, regional and global levels, including helping to clarify issues for cutting-edge research, technologies and innovation. Thus, IAP will revisit the issue addressed in this report in coming years to assess progress and needs for adjustment.

(iv) Science and technology capacity-building – within the broader community, at national, regional and global levels, including contributing to enhancing collaboration and building critical mass.

Outlook

IAP sees the need to be more ambitious in identifying the scientific opportunities for sustainable and healthy diets. Agriculture and food systems are vital for achieving most of the 17 Sustainable Development Goals, including those of ending hunger and extreme poverty by 2030. There is need to catalyse and coordinate new commitment to research and innovation, and to mobilise those resources in engagement between the scientific community, policy-makers and other stakeholders. Global and local sustainability of nutrient availabilities and utilisation and water are at risk under climate change and economic and political disruptions. Achieving healthy populations requires national actions supported by new international approaches to food systems' improved functioning. These are to be increasingly science and knowledge based, as addressed in this report.

1 Scope and scale of the scientific opportunities

1.1 Introduction

Tackling malnutrition in its various forms – undernutrition, micronutrient deficiencies, overweight and obesity – is a problem faced by all countries. Few challenges confronting the global community today match the scale of malnutrition, a condition that directly affects one in three people (IFPRI, 2016, 2017a). According to the Food and Agriculture Organization (FAO, 2017; and in collaboration with other United Nations (UN) agencies, FAO, IFAD, UNICEF, WFP and WHO, 2017), if current trends continue, one in two could be affected by 2030, in stark contrast with the objective to end all forms of malnutrition by that time.

The transformation of agricultural production towards economic, social and environmental sustainability is a global issue, connected with other challenges, for example poverty reduction, employment and demographic change, in particular. Resolving issues for food and nutrition security (FNS) can make a major contribution to the broader development goals. In this report, we describe how science has the potential to find sustainable solutions for national and global food systems relating to the complex issues spanning health, nutrition, agriculture, climate change, environment and human behaviour.

Academies of science have a substantial history of interest and achievement in these areas. The present work by the InterAcademy Partnership (IAP), the global network of the world's science academies, brings together established regional networks of academies, forming a new collaboration to ensure that the voice of science is heard in addressing societal priorities. Academies of science worldwide are committed to strengthen the evidence base to enhance FNS. In this collective academy work, we aim to communicate strong consensus, evidence-based messages about the global opportunities and challenges while also facilitating learning among regions, to show how our academies can share evidence, experience and ideas and implement good practice in clarifying controversial topics. We focus on the priorities for generating and utilising the knowledge base as a resource to support innovation and inform and shape the choice of policy options.

We recognise that much of the relevant policy happens at the national and regional levels but the present report takes a global focus: exploring collective action for what individual nations and the private sector cannot or will not do. Our focus draws on two principal policy perspectives, relating to the following:

(i) International public goods – those that have to be provided on a scale that is beyond individual countries' capacities and can be achieved better collectively. For example: constituting the dynamics of trade and the architecture of global markets; prevention of major food crises; competition policy and standards for foreign direct investment, transboundary natural resource management, transboundary food safety and other regulations and, most importantly for this report, the generation and use of science and innovation for facilitating FNSA. The global perspective on public goods is further warranted because national and regional competition acts to drive externalisation of costs to human health and the environment. We recognise that some would contend that action at national or regional level is sufficient in most cases – and we agree that there is much more that needs to be done to deliver coordinated policy and governance at these levels – but throughout the report we try to identify where international and global action and sharing will add value in tackling societal priorities. We also emphasise that national and regional activities must underpin and augment global solutions.

(ii) Risk and its transmission – international public goods are needed to address the risks of an uncertain world that is rapidly connected. The global threats are considerable and diverse including external effects on food systems, particularly climate change, pollution and growth of antibiotic resistance in farming. However, there are also shared opportunities, for example from advances in the biosciences, digitisation, and during rural and urban transformation. We emphasise in the report where research (including in the social sciences and humanities) and action are needed to tackle political and economic risks as well as risks for agricultural productivity and the other integral elements within food systems.

The global issues that we cover in our report are relevant to all countries and, to emphasise the relevance of our priorities, we discuss how our analysis maps onto the UN Sustainable Development Goals (SDGs).

There have been many other reports on the issues for FNS, stimulated variously by concerns about the burden of disease, a desire to understand the complexity of malnutrition, the increasing concerns about environmental, economic and societal stability, but also by the realisation of the transformative value of science and technology. It is on this last dimension that our report focuses.

The current IAP initiative is innovative in bringing together regional perspectives, drawing on the best science, and in this analysis connecting the regional insights to global opportunities and challenges. In this project, we utilise academies' convening, evidence-gathering, and analytical and advisory functions to explore the manifold ways to increase FNS. A core part of our work is to ascertain how research within and across multiple disciplines can contribute to resolving the issues at the science–policy interface, in particular in evaluating and strengthening agriculture-nutrition-health-environment linkages. Food systems are in transition and in our project design we have employed the integrative food systems approach to encompass, variously, all the steps involved in the value chain and its research, from growing to processing, transporting, trading, purchasing and consuming.

1.2 Global challenges for FNSA

According to the latest assessment by the UN (FAO *et al*., 2017), the number of chronically undernourished people in the world increased from 777 million in 2015 to 815 million in 2016. In addition, many more suffer from micronutrient deficiency and from the disorders associated with being overweight or obese. The food security status has worsened in particular in parts of Africa, South-East Asia and Western Asia, most notably in situations of conflict and in combination with droughts or floods. These growing causes of food insecurity associated with conflict and climate underline the need to include more social sciences, health and climate sciences in the global food, nutrition and agriculture research agenda to understand the issues and the options for their resolution. Earlier data from the global reports of the International Food Policy Research Institute (IFPRI, 2016, 2017a) indicated significant progress in many countries in reducing calorie deficiency but less progress on tackling micronutrient deficiencies. For example, anaemia affects about 2.5 billion people and child undernutrition is still a major contributor to disability-adjusted life years loss in Africa. At the same time, increasing numbers of people, including children, are overweight or obese and many consume calorie-dense but nutrient-poor diets. There are now more obese than underweight people in the world (NCD Risk Factor Collaboration, 2016). The relative public health burdens of overweight/obesity and hunger/micronutrient deficiencies should not be quantified only in terms of prevalence. It is also necessary to explore relative effects on morbidity, longevity, lifetime social and healthcare system costs and the inter-generational impacts. Diet-related non-communicable diseases (NCDs) are a major nutritional challenge (Reddy, 2016) and an increasing global health problem.

The desired outcome for FNS is access for all to a healthy and affordable diet that is environmentally and culturally sustainable[1]. In the regional work undertaken for this IAP report, all aspects of the triple burden of malnutrition (hunger and malnutrition, micronutrient deficiencies and overweight and obesity) have been covered, emphasising the goal of sustainable and affordable healthy food.

Major global challenges for delivering FNS are compounded by the pressures of growing population, urbanisation, climate change and other environmental change, economic inequality and market instability. All regions are facing environmental degradation, including loss of essential land and water resources. Setting priorities for increasing agricultural production must take account of pressures on other resources and the critical imperative to avoid further depletion of ecosystem services and biodiversity. According to the World Bank, approximately 11% of the Earth's land is used for arable purposes – that is, under cultivation – with a larger percentage, more than one-third, agricultural (including pasture and grazed forest lands). Although land is a primary requirement, modern agriculture is also heavily dependent on energy, water resources (particularly ground water), soil quality and infrastructure investments, ranging from transport to research and education. Innovation is crucial in the strategy for tackling the challenges of FNS but it is worrisome that the pace of technological advance may be slowing owing to static public investment in some countries.

Malnutrition is the biggest risk factor for the global burden of disease. Although the global emphasis on tackling malnutrition in all its forms emerged only relatively recently, the nature and magnitude of the challenges have been well described (for example, IFPRI, 2016, FAO *et al*., 2017) and, in principle, are understood by global institutions, including at the highest level, for example as discussed in the briefing to the UN Secretary-General (Scientific Advisory Board of the UN Secretary-General, 2016), where the need for a comprehensive approach is acknowledged. The SDGs adopted by the UN in 2015 provide a crucially important framework for clarifying and meeting the challenges but require fresh engagement by science to resolve the complexities of evidence-based policies and programmes and to underpin solutions: moving from blueprint to delivery. Agriculture and food systems are key vehicles for achieving SDGs (Omilola and Robele, 2017).

Although many countries have continued to make progress in addressing malnutrition targets (IFPRI 2016,

[1] Food security as defined by FAO occurs 'when all people, all of the time, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life'. According to FAO, food security covers the issues for food availability (is there enough?), access (can it be reached?), affordability (at a fair price?), quality (is it edible?), nutrition (as part of a balanced diet) and safety (could it harm health?).

2017a), many problems remain (FAO *et al.*, 2017). Furthermore, despite improved food access in some regions, diet quality is declining in some respects, compounded by continuing problems of affordability. The drive for calories in food production is causing health challenges, including obesity. Subsequent chapters in the report will assess the environmental and health implications in more detail to address the following question: in what ways might calorie-rich food harm us? In association with the global trend to an increased proportion of calories sourced from energy-dense foods, national food supplies around the world are becoming increasingly similar in composition. This increased homogeneity and reliance worldwide on a small number of crop plants decreases resilience (Bullock *et al.*, 2017), heightens vulnerability of national food systems and interdependence among countries in their food supplies, and gives urgency to nutrition development priorities aimed at increasing FNS (Khoury *et al.*, 2014).

A coherent strategy to deliver FNS must encompass both supply-side and demand-side issues. Reducing food loss and waste will help to relieve pressure on land and other natural resources. Modifying overconsumption will also help, not least in mitigating climate change, as will be discussed subsequently. It is vital to take an integrative food systems perspective and to identify the inter-related issues for resource efficiency, environmental sustainability, resilience and the public health agenda, while also taking account of the local–global interconnectedness of systems. The complexity of FNS needs to be understood by the application of systems analysis: this implies the use of models, which have to be sufficiently sophisticated and inclusive to avoid proposing solutions that would generate unintended consequences. The impediments to FNS vary between regions, countries and sectors: systems analysis can be employed to derive a research and education blueprint to inform the multiple solutions required. The outputs from multi-sectoral systems analysis can then be used to prioritise context-specific research and development (R&D), educational reforms and extension services.

Governments worldwide have implemented various policies to promote sustainable food systems and reduce the burdens of malnutrition but it is often difficult to evaluate the extent to which policies support the various dimensions of sustainability. New tools are being introduced to evaluate sustainable diets and food systems (Downs *et al.*, 2017), alongside efforts to map the present data gaps. As will be discussed later in this report, there are policy disconnects to resolve as part of the broader consideration of synergies and trade-offs between the economic, health, social and environmental objectives.

Although the importance of science and technology is often recognised, there is much more that can and should be done worldwide to address key global challenges:

- To act on present scientific knowledge to support innovation and its dissemination, and to improve robust policy development and coherence.
- To build scientific capacity and partnerships to close knowledge gaps, emphasising the core roles of basic science and of interdisciplinary initiatives.

1.3 Science and technology advances can strengthen the evidence base

Continuing with business as usual will not meet the global FNS and NCD targets agreed by the international community. There is urgent need to strengthen evidence-based policies and programmes and invest in new initiatives to gain new knowledge. Of course, many factors are involved in attaining FNS, a political choice that must involve businesses, civil society, aid donors and others at all levels, as well as policy-makers. It is our view that science and technology occupy a central place in addressing future FNS – in both the analysis of problems and in finding solutions – and this will be the main emphasis in our report: '*Our world is empowered by science as never before*[2]'. Science has a transformative role; in addition to the particular opportunities that are the subject of our report, science, technology and innovation are also essential more generally in efforts to eradicate poverty, protect the environment and accelerate the diversification and transformation of economic conditions.

Science has already made a very great contribution to agricultural productivity, where the rate of return on R&D has been estimated to range 20- to 40-fold (Beachy, 2014). However, rates of gain are declining as the potential of the older technologies is fully exploited. It is important now to be even more ambitious in identifying and using the scientific opportunities: to inform farming, encourage responsible innovation, and develop evidence-based regulations to enable further advances. It is also important to be more ambitious in using the science base to explain how issues for agriculture, food systems and environmental resources must also be part of the strategy for public health (Jones and Ejeta, 2016). The rate at which promise is turned into practice must accelerate. It should be appreciated that capitalising on scientific opportunities is something

[2] Declaration of the 8th World Science Forum on Science for Peace, 10 November 2017: https://worldscienceforum.org/data/cikkek/110/1100/cikk-110045/Declaration_leaflet_E.pdf.

that should pervade public policy widely. It is not just a matter for those involved in funding and prioritising the research agenda. Moreover, the participation of the private sector in agri-food research is of increasing importance in much of the world. In the countries of the Organisation for Economic Co-operation and Development (OECD), private investment in R&D accounts for about 60% of the total (Pardey *et al*., 2018). In other countries, private investment may be at relatively low levels but is growing and is increasingly important in the relationship between public institutions and private companies for the development and commercialisation of technologies in agriculture. It is, of course, important to ensure responsible innovation in all sectors—for example to avoid introducing new barriers to access by small-scale farmers to newly commercialised seeds. We consider some of the issues for responsible innovation subsequently.

Throughout the chapters in this report, we will exemplify specific research dimensions, particularly where initiatives in one region can usefully be extended worldwide. Key research questions of importance to the future of global agriculture and food systems have been analysed in detail and aggregated elsewhere (for example, Pretty *et al*. (2010) and in the four regional academy network reports that underlie this global synthesis)[3]. It is not the purpose of the present report to duplicate that previous, comprehensive analysis. However, we highlight general points that illustrate some of the scientific opportunities now coming within range. It is acknowledged that countries vary greatly in their current resources for science and innovation to tackle FNS. Nonetheless, we emphasise the importance of the following points to all countries for sustainable and healthy diets:

- While it is generally recognised that a global food system is emerging in the 21st century, a comprehensive global research system on food, nutrition and agriculture, drawing on a wide range of science disciplines and data, still needs to evolve. Academies can play a key role in shaping it. Among the strategic priorities are ensuring the coordination of research funding initiatives to address priorities, building of capacity for interdisciplinary work and at the science–policy interface.

- As the foundation for all other scientific endeavour, the commitment to basic research is essential to characterise new frontiers. This must be accompanied by long-term commitment to investing in research, including in developing countries, if innovative outcomes are to be realised. There is urgent need to build critical mass in research and innovation, and to mobilise that resource to tackle the agreed societal priorities. Historically, research has been concentrated in parts of some regions. Now, the building of critical mass must be a global endeavour and the voice of researchers worldwide must be heard and acted on.

- Although science delivers an excellent return on investment, it can be costly for some countries to develop sufficient infrastructure and human resources. It is important to seek ways to reduce unnecessary competition and duplication while increasing cooperation at large scale in research endeavours and attracting talented young people as the next generation of researchers.

- Basic and applied sciences have moved closer together, exemplified by the rapid advent of cutting-edge technologies. Thus, there is an increasingly robust scientific underpinning of emerging technologies in agriculture such as the novel bioscience-based approaches to improve plant and animal breeding and the suite of activities encompassed within precision agriculture. These cutting-edge technologies are vitally important but the scientific advances bring concomitant challenges—for education, regulation and the revival of farming extension services. Ambitious proposals now being made to sequence DNA of all life on Earth would generate an unparalleled resource for agriculture. However, advances in the natural sciences alone will be insufficient. There is also great need for research advances in the social sciences and humanities to tackle the associated food system challenges relating, for example, to institutional resilience, the determinants of decision-making and technology uptake, and the impact of trade policy (Teng *et al*., 2015). Social sciences research is also important in answering other fundamental questions, for example those associated with agricultural yield gap analysis, particularly with regard to socio-economic determinants to understand the wider social, financial and political contexts that shape farmers' decision-making (Snyder *et al*., 2017).

- It is time to act on the increasing insight on how to adapt food systems to climate change and how to mitigate their contributions to climate change, while also improving public health. Research on climate and food – whether in the natural or social sciences – should not be done just in locations that are easily accessible or familiar, but also where there is greatest need, for example to provide information to smallholder farmers (Anon., 2017a).

---

[3] A recent report from the US national academies (National Academies of Science, Engineering, Medicine, 2018) provides a further comprehensive analysis of research breakthroughs that are needed to tackle the urgent challenges and advance food and agricultural sciences by 2030.

- The increasing recognition of objectives for improving the science base for food systems overall – including the processing, storage, distribution and marketing of food products – requires a research agenda that goes beyond the usual framework for rural and agricultural development and mandates concerted intervention of science, engineering, technology and innovation. Food system transformation also brings research opportunities to focus on governance and coordination of policies, including health policy.

- To maximise the potential value of research, there must also be greater efforts to develop effective approaches to collect, standardise, curate and share big data sets. The present scarcity of large data sets, constructed according to comparable and verifiable methodologies, inhibits the design of policy and the efficient implementation of programmes, the assessment of their impact and the assurance of accountability.

- In keeping with the SDG Agenda 2030 commitment to '*leave no one behind*'[4], actions for the research agenda should empower and promote the social, economic and political inclusion of all members of society, being mindful to reach out to those who risk exclusion because of age, sex, disability, race, ethnicity, origin, religion or economic or other status. For this reason, we include priorities for vulnerable and marginalised groups and actions to reach, benefit and include these groups in efforts to improve their FNS.

1.4 Design of the IAP project and this report

In this IAP project, four regional academy network working groups were constituted, in Africa (Network of African Science Academies, NASAC), the Americas (InterAmerican Network of Academies of Sciences, IANAS), Asia (the Association of Academies and Societies of Sciences in Asia, AASSA) and Europe (European Academies' Science Advisory Council, EASAC). Each had an ambitious mandate to analyse current circumstances and future prospects, share evidence, clarify controversial points and identify knowledge gaps. Each region was invited to proffer advice on options for policy and practice at the national and regional levels, customised according to local circumstances and strategic needs so as to make best use of the resources available. Each working group consisted of experts from across the region nominated by IAP member academies and selected to provide an appropriate balance of experience and scientific expertise. The project design is novel in terms of its regionally based format and its objective to catalyse continuing interaction between and within the regions. It constitutes a 'bottom-up' analysis.

The four regional groups worked in parallel and proceeded from a common starting point represented by an agreed IAP template of principal themes. Among the main topics examined were the science opportunities associated with the following:

- Ensuring sustainable food production (land and sea), sustainable diets and sustainable communities, including the issues for agricultural transformation in face of increasing competition for land and other natural resources.

- Promoting healthy food systems and emphasising the focus on nutrition, with multiple implications for diet quality, vulnerable groups and informed choice.

- Identifying the means to promote resilience, including resilience in ecosystems and in regional and international markets.

- Responding to, and preparing for, climate change and other environmental and social change.

The four published regional outputs will be introduced in further detail in Chapter 2 and referred to throughout the following chapters. These publications are now being used at national and regional levels for engaging with policy-makers and other stakeholders. They are also a crucial resource in preparing this present, fifth report (Appendix 1). The purpose of the present report is to use these regional resources to inform discussion and action at the global level: to advise on inter-regional matters, local–global connectivity, and those issues at the science-innovation and science–policy interfaces that should be considered by inter-governmental institutions and other bodies with international roles and responsibilities. The IAP project and this report are intended to be distinctive and add value to the large body of work already undertaken by many other groups.

The project was formulated so as to stimulate the four regional networks in diverse analysis and synthesis according to their own experience, expertise and expectations while, at the same time, conforming to shared academy standards of clear linkage to the evidence available. It was anticipated that the regional work would accrue diverse evidence and might identify different solutions to common problems. The generation of this heterogeneity is regarded as a strength of the novel project design and this expectation of diversity has been satisfied. Nonetheless, while the regional outputs vary in detail in their approach, content and format, all

[4] Target 10.2 of the SDGs: https://sustainabledevelopment.un.org/sdg10.

provide highly valuable assessments as a resource for this fifth report.

1.5 What steps have already been taken to address the challenges of improving global FNS?

Many of the issues raised in the preceding sections have, of course, been discussed elsewhere, many times. Too often, however, well-intentioned initiatives have started in isolation – geographical, sectoral or disciplinary – or have been dominated by vested interests. We are sure that there is still need for new global, inclusive discussion, informed by verifiable evidence. New work must emphasise the necessary linkages across fragmented policy areas, all sharing a common dependency on excellent science. Our aim is to be policy-relevant without being overtly policy-prescriptive. Rather than bringing forth a wish list of ideas, we argue for a rigorously planned approach to FNS, emanating from integrated, systems-based analysis and leading to a coherent strategy to guide research. We also emphasise that some technologies are manifestly so important that they must be vigorously supported now because there is significant opportunity cost incurred by delay.

Our report cannot be comprehensive in covering all relevant issues or in reviewing what has already been analysed by many other groups. Nonetheless, as one starting point to our IAP global synthesis work in the next chapters, we take account of recent outputs by some of the principal groups, listed in Appendix 2 and providing important background to concurrent major global initiatives, in particular the SDGs and the Intergovernmental Panel on Climate Change Conference of the Parties (IPCC COP) recommendations. The material included in Appendix 2 also helps to illustrate roles and responsibilities of the global institutions and opinion-leaders, who we seek to support in this IAP project. Although we cannot go into detail on knowledge gaps and controversies in the brief summaries in Appendix 2, it is worth noting that there is relatively little emphasis by these other groups on the crucial role of basic science that we introduced in section 1.3.

1.6 IAP's intended audiences

We direct our messages and recommendations to a wide range of audiences, which include the following:

- All those in the UN system who are concerned with tackling the issues we raise and others in their networks who are involved in addressing the SDGs.
- Other inter-governmental groups, for example G20, G7 and international membership bodies, for example the OECD.
- International research initiatives at global and inter-regional levels, for example IFPRI and other institutes of the Consultative Group on International Agricultural Research (CGIAR), the EU-Africa Research Innovation Partnership.
- International initiatives in the private sector.
- Audiences at the regional and national as well as global levels.
- Our academies, who will help IAP in sustaining the effort to catalyse further discussion and action.

The topics we cover are also, of course, of great interest to the general public, who IAP aims to reach through follow-up activities by the regional academy networks and individual academies.

In Chapter 2 we describe some of the general similarities and differences emerging from comparison of the outputs from the regional academy networks together with the implications in moving from the regional to global synthesis of issues. In subsequent chapters we provide more detail on regional perspectives and global considerations in relation to each of the core themes identified by IAP.

2 Assessing regional diversity and commonalities

'*Academies worldwide are committed to engage widely to strengthen the evidence base for enhanced food and nutrition security at global, regional and national levels.*' IAP (from the common Foreword to the four regional reports)

Before beginning to explore the global issues discussed in Chapter 1, we emphasise that it is important to understand the present differences within and between regions. Understanding diversity and the determinants of resilience within regions provides resource for systematic inter-regional/global approaches to tackling challenges for FNSA. The present chapter reviews some of the points that emerged from the regional analysis phase, but first we delineate the relationship between the themes of the IAP project and the global SDG framework.

2.1 IAP starting point: key themes for FNS mapped onto the SDGs

The links between FNS and sustainable development are embedded in the SDGs with a necessarily close relationship between different SDGs.

As noted in Chapter 1, our IAP project combines twin goals of delivering strong consensus messages at the global level with clarification of the scientific basis of current disparities in policy expectations, objectives and opinions in different parts of the world. Initial IAP collective discussion was used to formulate a common agreed template (Appendix 3) to inform and guide all four regional working groups. Necessary components of this shared template are to understand regional characteristics, to delineate significant opportunities and challenges where science can help to inform policy-making and serve as a resource for innovation, and to advise on how to mobilise this scientific resource. Our IAP template themes (numbered according to Appendix 3) can be aligned with specific SDGs; the primary linkages are shown in Figure 1, with reference to further discussion in the chapters of this report.

The more general IAP template themes, 1 (key elements in characterising current regional position), 2 (major challenges and opportunities), 3 (strengths and weaknesses of science and technology), 9 (impact of regulatory frameworks and public policy), 10 (inter-regional dimensions for collaboration), can be regarded as underpinning all SDGs and will be discussed, where appropriate, throughout the present report, including later in this chapter. Although Figure 1 shows some of the primary linkages, we recognise the underlying principle that all SDGs interact with one another as an integrated set of priorities. We also strongly adhere to the view (ICSU, 2017) that science-informed analysis of the interactions among SDGs is currently lacking but could support more coherent and effective science–policy dialogue and decision-making.

In the present chapter we introduce some of the diversity that has been revealed in detail by the four regional reports, together with some of the consensus messages. The complete list of recommendations from each of the four reports is provided in Appendix 4.

2.2 Variation within and between the regions

In designing this project, it was possible initially to take a trans-regional perspective in Africa and Europe because of the existing continent-wide activities and perspectives, and the previous experience of the academy networks, NASAC and EASAC, in working with the institutions of the African Union (AU) and European Union (EU). It was not possible to do this in the same way for the other regions. IANAS encouraged impressive individual academy work to produce national reports from 20 countries throughout the Americas and then integrated these analyses into a regional synthesis. AASSA convened its working group on the basis of four sub-regional Asian assessments (Australasia-Pacific Rim, South-East Asia, South Asia and Central Asia plus Caucasus region), again followed by collective synthesis for the region as a whole. Although, of course, there are many differences between nations and between regions, the overarching objective in designing the IAP project in this novel way was to devise a framework for learning from diversity.

Even though the state of FNSA varies greatly in detail within and between regions, substantial convergence can be detected—in the objectives to encourage healthy diets, produce more with reduced inputs and improve rural development. All regions also face structural transformation in agriculture and food systems.

All regions are diverse in terms of agricultural practices, food habits, science and technology infrastructure, economic growth rate, population growth rate, natural resources and biodiversity, nutritional deficiencies and in the political, institutional and social drivers. Within each region, to a greater or lesser extent, a small number of countries concentrate the bulk of the regional research capacities while other countries underinvest.

Variation within a region can be very great: for example, there is a 100-fold difference in gross domestic product (GDP) between Afghanistan and Australia in the region represented by AASSA. It is, of course, important to take account of the diversity within a region when composing regional conclusions and when generating

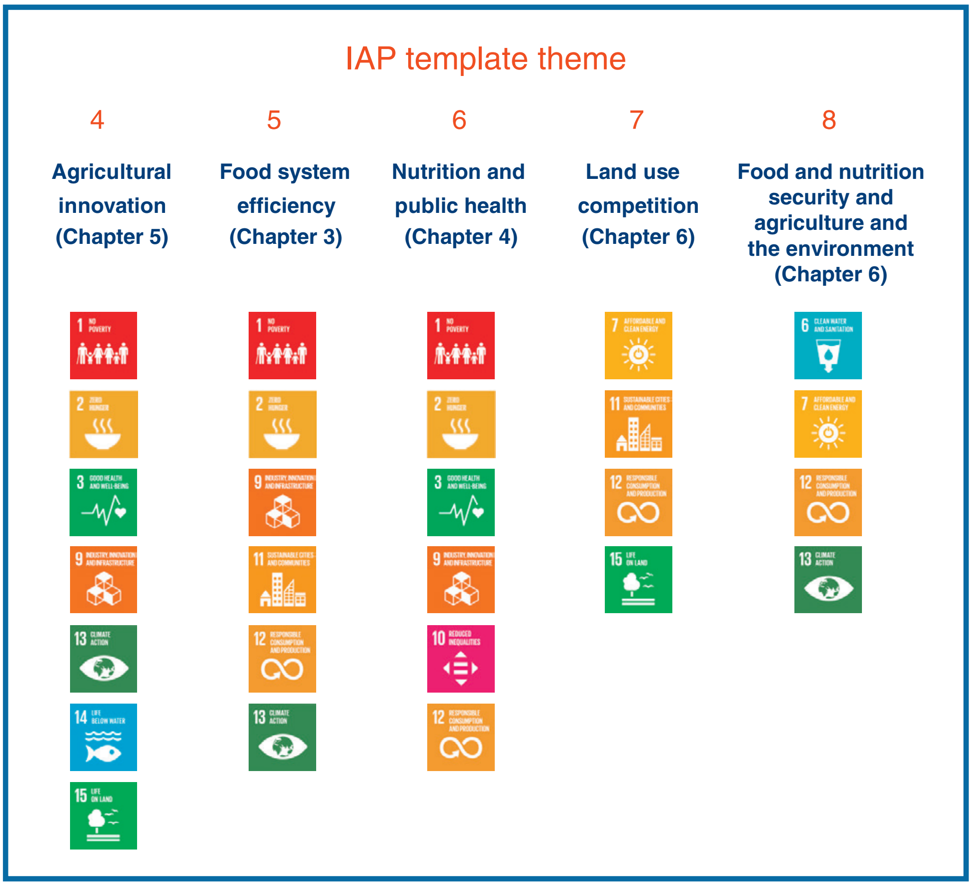


Figure 1 Mapping IAP project themes onto the SDGs.

global consensus messages. It is also the case that variation in FNS within a country is often greater than variation between countries, and a localised, territorial-based or sectoral-based analysis may be needed to understand the state of the drivers for FNS. This is discussed in detail, with accompanying case studies in the regional work, particularly by AASSA and IANAS. Some of the differences and similarities are discussed in more detail below, but the experience of the regional phase of the IAP project also emphasises the importance of introducing appropriate benchmarking and improved monitoring to do better in measuring and comparing between countries and regions, and over time.

2.3 Characterising diversity in FNSA

Demographic trends demanding increased food supply tend to be concentrated in parts of Africa and Asia. Countries particularly susceptible to future food and nutrition insecurity tend to be those characterised by current high levels of undernutrition coupled with high projected population growth, as reviewed by AASSA. To a significant extent, all regions share problems associated with other demographic changes, in particular ageing populations and increasing urbanisation. However, as will be emphasised subsequently, comparisons between countries are complicated by differing methods of characterisation of FNS and lack of assessment methods to uncover inadequate micronutrient intake. There would be value in more standardisation and consistency in constructing food composition databases, national and regional dietary surveys and markers of nutrition status.

Regions differ, in their agricultural productivity, access of farmers to knowledge and services, in the availability of uncultivated land, and in access to food by consumers. Some of the evidence for these regional divergences is discussed in detail in the academies' regional reports. FAO food assessment (FAO, 2016) indicates that 39 countries globally are in need of external food assistance. As described by NASAC, 28 of these countries are in Africa. Where agricultural transformation is taking place, for example in Africa, it is leading to tangible impact on economic growth, poverty reduction and hunger reduction, and NASAC observed that these changes attest to the power of having a prioritised, funded strategic plan for agriculture and food security.

Despite significant progress in the past decade, current famine zones in Africa and elsewhere (e.g. Yemen) demonstrate the fragile nature of FNS that can be quickly disrupted by civil conflict and wars. These current problems are not usually the result of a single shock (e.g. crop failure or conflict) but rather, as discussed by NASAC, these complex emergencies are the tipping point in the failure of a long-term development process. These situations leave many hungry and vulnerable to food shortages. Many people are then forced to migrate, leading to greater marginalisation and vulnerability to food shortages.

Regions may differ considerably in nutritional conditions but often share nutritional challenges, in particular the increasing availability of relatively cheap, energy-dense foods, contributing to obesity and NCDs everywhere and to micronutrient deficiency in some regions (see Chapter 4). Yet, food policy in many countries (as described by NASAC and IANAS) still focuses on undernutrition with regard to key micronutrient deficiencies and may pay less attention to problems of overweight and obesity. This was justifiable until relatively recently, but policy now requires additional emphasis on all aspects of FNS.

There is food and nutrition insecurity in all countries, even those with high GDP. For example, as discussed in the IANAS report, in the USA, 12.7% of households were classified as food insecure in 2016[5]. In Europe, as described by EASAC, the proportion of EU households unable to afford access to the minimum amount of energy and nutrients generally recommended in dietary guidelines has increased since 2010, after declining over the period 2005–2010. Recent FAO analysis[6] for Europe as a geographical area concludes that sustained economic growth is key to ensuring food security in the region. However, it should also be noted that, as demonstrated in the IANAS analysis, sufficient levels of agricultural production can coexist with severe food and nutrition insecurity, a conclusion also reached in earlier research on hunger and famine in Asia and Africa (Sen, 1981; von Braun *et al*., 1998). For the population of most European countries, the burden of overweight and obesity, in terms of disability-adjusted labour years, now far exceeds that from undernutrition.

The diversity in FNSA will be discussed in detail in subsequent chapters. In some cases, agricultural yields will need to be increased from what are considered currently to be high yields; in other cases, technology must be brought to bear to close appropriately defined 'yield gaps'. Despite the diversity, there is an essential shared objective: innovation.

2.4 Variability in scientific infrastructure and research capabilities

There are scientific strengths and weaknesses in all regions and there is a need everywhere to reduce the fragmentation of efforts both in conducting research and in using the outputs from research. Comparable recent data on the intensity of investment in agricultural R&D between countries and sectors are not always available. FAO (2017) provides detailed analysis for countries but the data are not very recent. Globally, agricultural R&D investment increased by about 3% a year during the period 2000–2009 with much of the increase accounted for by China and India, together with Argentina, Brazil, Iran, Nigeria and the Russian Federation. Global private sector investment in research and development in agriculture and food processing accounted for about 20% of the global total spend, but most of this occurred in high-income countries. Further discussion of the patterns of change in agricultural R&D investment is provided in Pardey *et al*. (2018).

The wide variation in national investment in science and technology within a region is well illustrated in Asia where AASSA analysis classified countries into four categories:

(i) Mature science and technology cultures where investment in performance is globally competitive although recent increments in funding are now beginning to level off.

(ii) Advanced developing science and technology cultures – for example India and China – that have made major commitments to academic and industrial agricultural research infrastructure, including basic research, but integration between public and private sectors is often difficult.

(iii) Developing science and technology cultures where R&D spending in proportion to GDP is still low but increasingly emphasised with some excellent international centres. Most R&D for FNS is goal based and leading scientists are still often trained abroad.

(iv) Countries with limited science and technology capacity, and the sustained political will for investment in science remains to be established.

Similar diversity can be found in Africa and in the Americas, although almost all countries have one or more agri-food research institutes. These institutes often represent the bulk of the agri-food research capacities. Private sector research also plays a larger role in those countries (such as the USA and Canada) that also have high levels of public sector investment. Detailed analysis

[5] https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-us/key-statistics-graphics.aspx.
[6] The State of Food Security and Nutrition in Europe and Central Asia, 2017.

in the IANAS work identified problems, particularly in Latin America and the Caribbean with regard to the following:

- Insufficient infrastructure in scientific equipment and facilities.
- Inadequate integration of programmes in setting priorities.
- Relatively low numbers of researchers – and the ageing of the cohort makes generational change difficult.
- Inadequate databases to characterise the status of the agricultural system.
- Lack of collaboration between universities and research institutes and weak interaction between researchers and the demands of the private producer sector, and between researchers and extension services, and the needs of vulnerable populations.

These problems are compounded by insufficient funding for research and are shared by many other countries in other regions. In the Americas, there are examples of international cooperation schemes between countries at different levels of economic development and these schemes can represent a significant part of the agricultural research capacities.

Detailed analysis by NASAC showed that national spending on agricultural R&D in Africa is often low compared with elsewhere and that African countries may focus on adapting technologies developed elsewhere to local needs. The NASAC assessment indicated that the reliance of African countries on external funding may place them at a disadvantage in terms of capacity building (human, technical, institutional and infrastructural) to exploit science and innovation opportunities and apply best practices at scale. NASAC also noted that agricultural research spending is becoming more dependent on volatile donor funding and that important aspects of policy development, for example establishing comparable baseline data, monitoring and evaluation, are not resourced in most countries. Also, in many cases, those responsible for research policy operate in isolation from other policy sectors or agencies, and links with the private sector are often weak. However, there is increasing recognition in Africa, as in the other regions, of the critical role played by science, technology and innovation in economic growth, and many African countries have introduced agricultural development plans. Nonetheless, R&D investment and research capacities are still concentrated in a small group of countries—Nigeria, Kenya and South Africa account for half this investment.

In Europe, and in Africa to some extent, there is also regional-level research funding. The variety of trans-regional instruments to support collaborations in public sector research is discussed in detail by EASAC, and this trans-regional capacity also serves as a stimulus to public–private partnerships in research and innovation. Trans-regional capacity may also support research collaboration with other regions. For example, the EU-Africa High Level Policy Dialogue on Science, Technology and Innovation (2016) provides a roadmap for jointly funded research and innovation on FNS and sustainable agriculture that emphasises shared interests in sustainable intensification, food systems and nutrition, agricultural markets and trade. The joint commitment developed in this EU-Africa model might serve as a basis for other inter-regional and global partnerships: currently there is little or no equivalent trans-regional research funding and collaboration in Asia or the Americas (see subsequent chapters for recommendations by AASSA and IANAS). This lack is not necessarily filled by international bodies with regional responsibilities. CGIAR very usefully fills a void where national or regional funded research may be lacking and it is important to increase the commitment to CGIAR centres and national centres of excellence, concentrating on goal-oriented research. However, there is also a need for further international commitment to basic, 'blue skies' research as a fundamental source for discovering new directions and applications. Potential solutions to building research critical mass, and enhancing collaboration at the regional and global levels, are discussed in subsequent chapters and summarised in Chapter 7.

2.5 Variability in linkage of research outputs with development of policy options

One major difference between the regions is the degree to which policy-making is undertaken at the regional level. In the EU, there are established institutions (European Commission, Parliament and Council), in Africa regional activity is maturing rapidly at the AU level, but there are no equivalent trans-regional platforms in Asia or the Americas—and national linkages between the science and policy communities vary widely. The Organization of American States (founded 1888–1890) is the world's oldest regional organisation and does serve to coordinate and promote cooperation among the countries of the Americas. But it does not have quasi-governmental powers and has only limited impact on national FNS policies.

There are regional responsibilities, of course, within the global inter-governmental organisations, in particular the UN system, but these have different accountabilities and distinctive internal advisory mechanisms. The trans-regional institutions in the EU, and increasingly in Africa, provide an opportunity for building strong relationships between the broader scientific community, the policy community, and other stakeholders. The options for building equivalently strong relationships in other regions and at the global level, and how academies might contribute, will be discussed further in Chapter 7.

2.6 Consensus between the regions and policy implications

Notwithstanding the great diversity within and between regions, the four regional contributions to this global phase of the IAP work agree on numerous points. Many of these consensus points will be discussed in further detail in subsequent chapters, for example the following:

- There are major scientific opportunities for innovation in agriculture to improve efficiency. There must be increased focus on nutrition-sensitivity in policy-making across various sectors.

- All regions will probably continue to demonstrate increasing demand for processed food as a result of demographic changes (growing population, increasing proportions of middle class and urbanised, more women in work). Processed food with longer storage life and requiring less cooking brings new challenges for food technology and for ensuring food safety, but also provides opportunities to lessen food wastage.

- It is vital to take a broad view of FNS, in the food systems approach, and to recognise the need to take account of the issues for provision of other ecosystem services and the pressures on other environmental resources. This requires more to be done to develop indicators to measure progress in sustainability and other societal objectives.

- In all regions, climate change is already leading to significant adverse impact on agriculture and food systems, and this impact is expected to increase. There will, of course, be variation in impact within regions. For example, in Europe climate change is expected to improve the suitability of northern Europe for growing crops but to reduce crop productivity in large parts of southern Europe (European Environment Agency, 2017). We explore the consequences of regional variability in greater detail subsequently.

- Current databases on FNS are not sufficiently robust and this weakness is a constraint on research. For example, in many countries there are no time-series surveys to identify the prevalence of food deficiencies at household level or to characterise subsets of the population.

- It is agreed that sustainable agriculture should be a priority in the bioeconomy and there is need for better integration of strategic actions across sectors in pursuit of the bioeconomy.

All regions share many elements of a diverse policy agenda relevant to FNSA. In subsequent chapters we will highlight both the food systems' and health systems' perspectives. Food and agriculture policy cannot now be considered independently from other systems (Box 1). There is also agreement on the common determinants of shaping effective policy and effective policy interconnections, in particular the basis in sound evidence and systematic data collection and the need to update policy options in consequence of assessment of the outcomes of previous policy implementation.

Box 1 Common policy requirements identified by all regions

Policies that:

Help to redesign the whole agricultural economy, for example land use, other rural development, recycling, fisheries, for increased efficiency and sustainability.

Provide framework for research and technological or other innovation in food systems e.g. introduction of new raw materials, regulation of pesticide and antibiotic use, animal welfare, organic farming, new approaches to breeding.

Promote the bioeconomy and responsible innovation across sectors.

Build human resources, for example education and training, attracting young people to work in food systems and research, addressing labour gender issues.

Promote consumer rights, for example in consumption of sustainable healthy food, and regulation of food safety and food labelling.

Manage access to food, for example in social care systems.

Promote health, especially for specific groups and vulnerable populations, and consider specific cultural and societal needs.

Address other environmental aspects, for example climate, energy use, water availability and quality, soil, habitats and biodiversity.

Mediate inter-regional relationships, for example trade agreements, development aid.

The list in Box 1 reflects a mix of requirements for national, regional and international policy instruments. The present report focuses on the international level with regard to matters at the science–policy interface, but we recognise that a coherent strategy depends also on coordination of national and international efforts. Unfortunately, the complexity of policy requirements can act to deter action: scientific analysis of the complexity necessitates inter- and trans-disciplinary work.

NASAC observed that the heterogeneity in the distribution of natural resources and disparity in the levels of economic development within a region may make it difficult to construct each public policy to be valid for an entire region, and the same reservation applies at the global level. What is important, therefore, is to focus on the issues and opportunities that are common to all countries in reflecting on how to frame the policy agenda to address FNS for all. Coordination is also dependent on an appropriate institutional architecture to enable policy reviews, reforms and implementation.

2.7 From regional analysis to global priorities

Solutions to food-related problems are often context-, region- and culture-specific. Some of the outputs from the work of the regional academy networks were specific to locality, but others were global in their relevance. Here we focus on inter-regional and transboundary matters relating to resource issues, again in the context of our initial perspectives on international public goods (especially science and technology) and risk transmission.

Recent trends have increased globalisation of the agricultural economy. What had been individual country problems now become global challenges. For example, increased migration, conflicts and political instability partly flow from inadequate resources and productive capacity, and the spill-over to other countries is well documented. An increasing homogeneity in global food supplies, with ever greater reliance on a limited number of staple commodities, may also be associated with a loss of resilience to perturbations, introducing systemic risk for an increasingly monolithic food system.

Every country is co-dependent to a greater or lesser extent on local production and global trade. As observed in the NASAC work, over-reliance of some African countries on imports to meet the local demand, for staple foods in particular, makes these countries vulnerable to economic risks, insecurities and uncertainties and threatens long-term resilience. AASSA discussed the Asian experience of countries such as Japan and South Korea, with low self-sufficiency and currently relying successfully on food imports but vulnerable to international food shortages.

In addition to production and trade flows, global knowledge flows are growing in importance. Understanding this plurality of interconnections between local and global systems draws attention to a wide range of issues for trade networks, land use, climate change impacts and the health–nutrition–sustainability interfaces. As discussed by EASAC, countries and regions have a responsibility to ensure that measures taken to satisfy domestic FNS do not create additional problems for other countries in terms of their use of land, water, energy, fertiliser and other resources or their ability to innovate and export.

What are the future prospects? There have been many attempts to construct scenarios or use other foresight initiatives to model future global developments in FNS. One major analysis of projected trends by FAO is described in Appendix 2; another by the World Economic Forum, based on market dynamics and demand shifts, is discussed in the EASAC report. In reflecting on alternative futures, it is desirable to embed flexibility to capture both the relatively predictable changes (such as population growth and urbanisation) and the critical uncertainties (including disruptive technologies). OECD work (2016) – assuming continuing rising food prices, declining contribution of agriculture to GDP, pervasive transboundary livestock diseases and food safety risks – encapsulates many of the analyses made by other bodies in their portrayal of three alternative scenarios for global food and agriculture:

- Individual, fossil fuel-dependent growth: a world driven by sovereignty and self-sufficiency with emphasis on economic growth and less on environmental or social questions. Cooperation is driven by national interests.
- Citizen-driven, sustainable growth: with an emphasis on environmental and social protection. Technologies focus on natural resource savings.
- Fast, globally driven growth: with a strong focus on international collaboration to achieve economic growth and less attention on environmental issues. Technologies flourish especially for food, feed and energy products that are easily shared internationally.

In our view, the value of these, or other scenarios, lies not primarily in the prediction of the most likely outlook but rather in the propensity to stimulate collective efforts to explore and enable robust but flexible policy responses to the anticipated challenges. Such studies also allow assessment of variation in future scenarios and give an indication of the magnitude and uncertainty of possible changes. This collective effort for policy preparedness must include generating and using scientific evidence – something to which the OECD gives

Box 2 Drivers of change affecting global food systems[7]

Population growth and other demographic changes, for example urbanisation, ageing of population, youth bulge in Africa, migration[8].

Pressures on dietary consumption and consumer values, including private sector strategies.

Governance and transformation of food systems, including new value chains and integration of markets.

Competition for key natural resources, including land and transboundary water.

Climate change.

Innovation, education, technology (including disruptive technology) and infrastructure.

less prominence in their 2016 publication but which is central to our IAP efforts.

Notwithstanding the point made earlier that a local analysis may be necessary to understand diversity, global food systems can be characterised as subject to a wide range of drivers of change (Box 2), all impinging on purchasing power and equity of access.

These drivers will be discussed in further detail in subsequent chapters. It should be emphasised that there is risk of the drivers outpacing the potential of food systems: to prepare for and diminish that eventuality, there is increasing need for risk assessment and coordination of policies across sectors and across governments. For example, national assessments of climate change impacts may not take fully into account the interaction and amplification from impacts elsewhere (Challinor *et al*., 2017)[9].

Global connectivity also means that a poor local policy response can exacerbate supply disruptions and create global impacts. Because significant net risk can result from interaction between individual risks of lower magnitude, there is need for better coordination of policies – across agriculture, environment, health, trade, food standards and foreign policy – to sustain systems resilience. Involving multiple sectors with different remits may not be easy, particularly as there is also crucial need to integrate internationally as well as nationally.

[7] There are major issues associated with poverty, food affordability and access that are not discussed in detail in the present report but were reviewed in regional analyses, particularly by AASSA and NASAC, together with determinants of marginalisation, such as gender. NASAC also emphasised the crucial role of agriculture itself as a driver of broader economic development.

[8] The interconnections between regions are complex. As observed by NASAC, substantial burden from people displaced by conflicts (or other reasons) is felt by neighbouring countries as well as by their country of origin. EASAC noted that the contributions of food insecurity in triggering societal insecurity globally has multiple implications for regions, including those associated with migration. The impact of conflict as a key driver for food crises is discussed in detail in the 2017 report (FAO *et al*.). FAO efforts on World Food Day 2017 also focused on issues for ascertaining the impacts of migration on food security and rural development (http://www.fao.org/world-food-day/2017/home/en/). The impacts of climate change are likely to continue impelling migration. Recent years have seen very large displacements of people and while short-term responses focus on humanitarian assistance, for the longer term it is essential to invest in food systems and rural development to change the future of migration.

[9] In particular, urgent policy action was advised by Challinor and co-workers (2017) to address two cross-border risks arising from climate change:

- Weather-related shocks to international agricultural production can contribute to food price spikes and reduce access to food for vulnerable groups.
- Climate-related displacements of populations can affect countries remote from the local risk.

3 Efficient and equitable food systems: defining the challenges, and the opportunities for innovation

'*Issues for improving access to healthy, sustainable food have to be considered within the wider context that includes the societal and environmental dimensions. … a systems-based view has to be taken on how to provide food and nutrition security sustainably, and policy-makers are beginning to see the necessity for moving from agricultural policy to a more coordinated food policy*'. EASAC

3.1 Scope and efficiency of food systems

The food system includes the production, transport, manufacture, choice and consumption of food, and its impacts on health, environment and society (including economics). Historically, both markets and policy have focused on driving agricultural efficiency (yield per unit inputs), partly in the assumption that this becomes a proxy for the efficiency of the food system. Arguably, however, excessively promoting agricultural efficiency risks incentivising the externalisation of costs onto the environment, and the over-production of food, leading to greater waste, and a reduction in the efficiency of the food system. This implies the need for a greater focus on the efficiency of the system in delivering health and well-being for people and the planet, as well as profits for the food system actors. An operational definition of efficiency might be the number of people fed healthily and sustainably per unit input (where units include natural and fiscal capital).

The four IAP regional academy networks agreed that increasing agricultural productivity is important but not sufficient to address the challenges for FNS. As observed in the NASAC work, for example, as populations become urbanised and markets more globalised, there must be increasing impetus for action not only at the level of production but across all stages of the food value chain. EASAC emphasised that developing an integrated approach – moving from agricultural policy to food policy – requires both clear definition of the components within the food system and better understanding of the trade-offs between different policy actions.

Furthermore, extending analysis from the efficiency and sustainability of agricultural productivity to food systems overall, also provides the opportunity to clarify and promote characteristics that can create synergy within the food system, understood as the web of value chains (i.e. value web). The improved use of big data and information flows can possibly facilitate new and deeper insights in consumer behaviour and environmental change.

In taking an integrated food systems approach to define the research agenda, the academy work emphasised key aspects for transformation of food systems that spanned agriculture, the circular economy and the bioeconomy (see also Chapter 7), and included the following:

- Agronomic practice – exploring issues for sustainable intensification, while seeking to diminish pressures on natural resources.
- Tackling food loss and waste, including using opportunities in food science and technology to improve processing, distribution and storage, promoting food safety.
- Responding to, informing and managing consumer demand and setting health targets.
- Understanding markets and the determinants of instability in the trade of agricultural commodities.
- Taking account of cross-cutting issues, in terms both of opportunities such as digitalisation and use of big data sets, and challenges. Regarding the challenge of climate change, there is need to evaluate climate resilience throughout food systems and transform those systems to mitigate their global warming impact (Porter *et al*., 2017).

The complexity of assessing the integrated linkages between policies for agriculture, food systems, nutrition and health, and determining the research priorities for these areas and for the linkage with global environmental change, have been described comprehensively in the literature (for example, Kanter *et al*., 2015; Horton *et al*., 2017) and are summarised in Figure 2.

There is accelerating momentum worldwide to adopt the food systems approach to bring consumption and production patterns together and to operate within the planetary boundaries[10]. Recent analysis by the Committee on World Food Security High Level Panel of Experts on Food Security and Nutrition (CFS HLPE, 2017) furnishes a wide range of recommendations across food supply chains, food environments (the physical,

[10] For example, the 10YFP Programme on Sustainable Food Systems: http://web.unep.org/10yfp/programmes/sustainable-food-systems-programme.

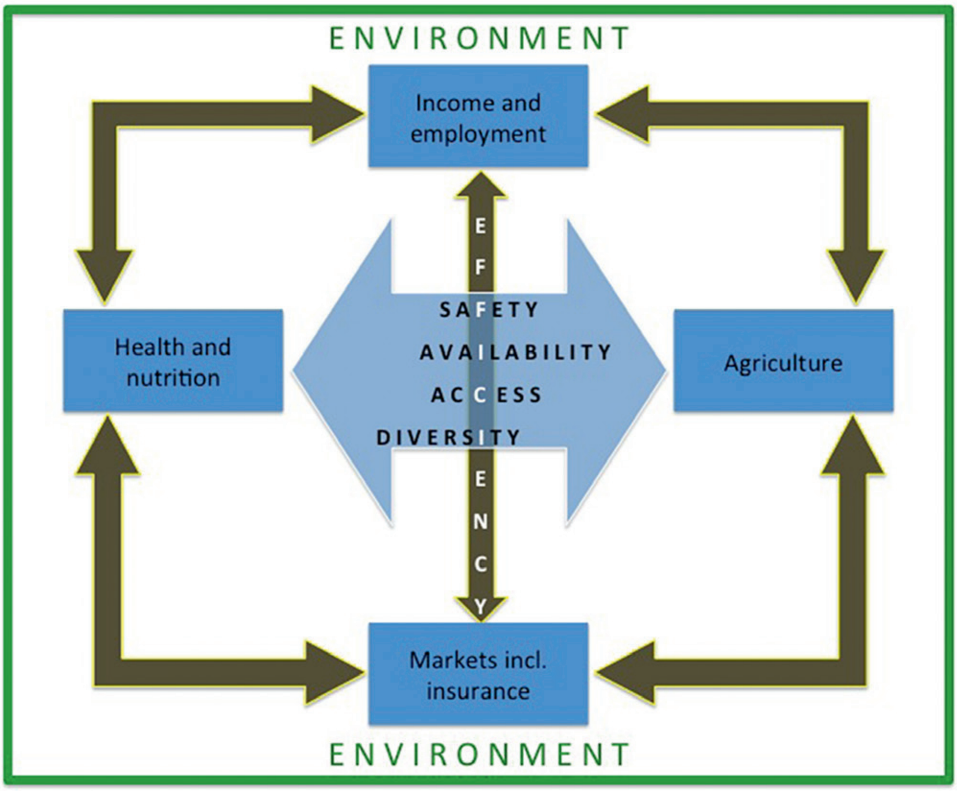


Figure 2 An aggregate conceptual framework for research on food, nutrition and agriculture within the food systems context (von Braun, 2017).

economic, political and socio-cultural context in which consumers engage with the food system) and consumer behaviour. Most of those HLPE recommendations focus on policy and practice although it is acknowledged that change also depends on new research and technologies and better access to existing technologies. The report from the International Resource Panel of the UN Environment Programme (IRP, 2017) calls for global resource-smart food systems to incorporate changes in the way food is grown, harvested, processed, traded, transported, stored, sold and consumed[11]. The report also covers a wide range of specific actions needed, including those to reduce food loss and waste, to move away from resource-intensive products and to promote the research and innovation agenda.

3.2 Circular and bioeconomy

Some of the specific policy issues raised in the regional reports can be encompassed within two broad strategic areas for food systems relating to the circular economy and the bioeconomy. As discussed by IANAS, for example, the circular economy is a model of reducing, re-using and recycling in production. This should promote environmental and economic sustainability and encourage value addition for processed foodstuffs and other products important in diversifying local economies. EASAC noted significant opportunities for reducing food loss and food waste in contributing to circular economy objectives and opportunities at the intersection of the circular economy and bioeconomy.

The emerging concept of bioeconomy offers opportunities to address societal challenges but measuring the bioeconomy is still in its infancy (Wesseler and von Braun, 2017). Research is needed to understand bioeconomy resources and product flows, to develop international certification standards and impacts on international trade. Research should also investigate the range of bioeconomy opportunities for developing countries, which so far have mainly concentrated on the bioenergy sector. As described by IANAS, the bioeconomy is based on intensive use of knowledge of biological resources, processes and principles for the sustainable production and conversion of biomass into products and services. This enables substitution of non-renewables by renewables—from both land and sea. The country case studies generated by IANAS exemplify the strong emphasis on the bioeconomy as a driver of value-added exports. Illustrated by recent activities in Europe as well as the Americas, and elsewhere, there is significant political momentum in developing and

[11] For further detail on the key strategies embraced within this systems approach, see 'Shifts towards resource-smart food systems': http://www.unep.org/resourcepanel.

Box 3 Proposed unifying principles for a global bioeconomy

1. *Global partnerships and integrated strategy.* International collaboration between governments, public and private researchers, essential for optimising resource use and sharing knowledge. For example, to support sustainable intensification.
2. *Assessing impact.* Identifying and developing ways to measure bioeconomy development and contribution to SDGs. In particular, a priority target is food security, and national monitoring should include the international dimension so that a country examines how its practices might affect others.
3. *Coherent policy aims and implementation.* Bioeconomy initiatives need to be linked more closely with multilateral policy processes, particularly SDGs, COP climate discussion and biodiversity agreements. A UN body on bioeconomy should be constituted to handle the coordination.
4. *Building human resources.* International collaboration is required to define the knowledge, skills and competencies required for developing a bioeconomy. This includes open learning platforms to allow sharing of curricula and training content.
5. *Learning from pathfinding initiatives.* R&D support programmes should encourage global collaborations in breakthrough projects e.g. food systems, sustainable aquaculture, artificial photosynthesis and global governance.

Source: adapted from El-Chichakli *et al*. (2016).

updating bioeconomy strategies to embrace agriculture and food systems.

Global analysis indicates that national and regional efforts to boost the bioeconomy are central to many of the SDGs (El-Chichakli *et al*., 2016). '*But conflicting national priorities make it hard to align bioeconomy policies to meet the SDGs on a global scale.*' For example, decisions on regulating bio-based products in the EU may impede producers elsewhere who lack the testing infrastructure for ecological certification. And strict bio-piracy regulations in some countries, aiming to protect biodiversity and traditional knowledge, are impeding international research in plant biodiversity. The analysis (El-Chichakli *et al*., 2016) suggests that there are five unifying principles that need to be agreed for a global bioeconomy (Box 3).

3.3 Climate change

The increased efficiency of food systems must occur in the face of various constraints (see Chapter 6). The land area available for production is unlikely to increase and may well decline because of the demands made, variously, by urbanisation, conservation and ecology, and land loss from sea level rises. There will be limitations in supply of other vital resources used by food systems, in particular energy, fertiliser and water. The challenges are exacerbated by climate change, a global risk in many respects[12]. Climate change significantly increases the volatility in the global food system, as shown in modelling for the main four food crops, wheat, maize, rice and soy, and reduces the incentives to invest in agriculture, owing to the increased risks (Halle *et al*., 2017).

All of the regional reports discuss the challenges of climate change for agriculture and the potential for adaptation and mitigation (see also Chapters 4 and 5). Action on climate change may provide the catalyst for initiating other changes to improve sustainability. The direct climate challenges to agriculture include erratic and extreme weather events – such as recurrent droughts and floods – as well as more gradual changes in temperature and precipitation, together with other pressures mediated by increasing incidence and severity of pests and diseases and impacts on beneficial organisms, for example insect pollinators.

The health effects of climate change are serious problems and can broadly be grouped as those related to the consequences from food supply and food quality changes, heat stress and air pollution: all of them are also affecting the food system (Pontifical Academy of Sciences, 2017). Modelling of global and regional health effects accruing from future food production under climate change (Springmann *et al*., 2016) predicts that in absolute terms most climate-related deaths would occur in South-East Asia, but no region is immune. The intra-regional range of vulnerabilities is exemplified by IANAS—from Canada, where tundra areas are under the influence of rapid warming, to countries such as Bolivia and Peru, suffering from extreme events, including both droughts and floods. The Caribbean countries are especially vulnerable to many impacts from climate change.

The IANAS report reviewed various approaches to building agricultural resilience to climate change. EASAC emphasised that the agenda for filling gaps in climate change research must also include the social sciences, for example to understand farmer and consumer behaviours, because climate-smart agriculture requires coordinated actions by researchers, farmers, the private sector, civil society and policy-makers to identify and introduce climate-resilient pathways. Increasing capabilities and

[12] For example, as discussed in the work of the World Food Programme at the time of COP 23 'How climate change drives hunger', 15 November 2017: http://www.wfp.org/content/2017-how-climate-drives-hunger. See also Myers *et al*. (2017) for a review of pathways for impacts of climate change on food systems and food and nutrition security.

resilience of food systems in the face of increasing uncertainty and instability is a priority for all regions and requires significant research and innovation to underpin an integrated approach that encompasses the sustainable use of natural resources (Chapter 6), improved crop and livestock productivity, diversification of livelihoods and the tackling of market variability. There are particular challenges for mixed farming systems, as discussed by NASAC, and there are gaps in knowledge about how interactions between crops and livestock may be affected by climate change. Filling these knowledge gaps, and determining how policy and governance can most effectively provide the required enabling environment, requires research on appropriate biophysical models of mixed systems, whole farm models and scenarios, and identification of measures to analyse adaptation success (Thornton and Herrero, 2015). The food system/value chain approach helps to provide a coherent basis for examining multi-faceted interrelationships in response to major drivers of transformation, such as the impacts of climate change. A recent analysis by the US Government's Global Hunger and Security Initiative (Fanzo *et al*., 2017) discusses the linkage between climate change and nutrition throughout food systems from production to consumption. Key recommendations from that analysis describe the importance of collecting data and conducting research to compose a robust evidence base to support action, and to assess the impacts of those actions. Our IAP focus on the scientific opportunities and challenges associated with climate change draws examples from the four regional reports. Issues for diet and nutrition will be discussed in Chapter 4, agricultural innovation in Chapter 5 and competition for resources in Chapter 6.

The remainder of the present chapter explores some of the other, downstream facets of the food chain and its environment within the food systems context.

3.4 Food waste and recycling

About 30% of food produced worldwide is thought to be lost during the various steps of production, harvesting, storage, transport, processing, marketing and consumption. In this report we use the terms 'food loss' or 'food waste' to include both losses and waste. The database on waste and losses needs strengthening across countries, in order to facilitate global learning and to design focused investments for mitigation. Food waste encompasses a large amount of energy, water and land resources wasted. SDG 12.3 aims to halve the per capita food waste. It should also be recognised that consumption in excess of nutritional requirements is also a form of food waste that has health as well as environmental costs (Alexander and Moran, 2017). Diverse issues for reducing food waste were covered in the regional reports and the emphasis varied, with NASAC, for example, focusing on the relatively early stages of crop harvesting and storage whereas IANAS and EASAC addressed waste in food systems at the level of retail systems and consumption[13].

Food waste is a major challenge to achieving FNS. Quantifying food waste is a major component in constructing the Food Sustainability Index[14], an instrument now being used to rank countries and reveal gaps in the present data (Downs *et al*., 2017). As recommended by EASAC, it is important to collect more robust data on the extent of waste in food systems and the effectiveness of interventions, to inform policy decisions, for example those appertaining to recycling and the circular economy. In aggregate, for the research agenda, it is important to do better in identifying where food is wasted, to breed crops with greater resistance to pests and disease (see Chapter 5), to explore ways to produce food with enhanced storage capabilities, to create smarter logistics throughout the food system and to develop better recovery and recycling technologies. As reviewed by EASAC (and discussed further in the next chapter), scientific advances are now also bringing new methods to authenticate the integrity and traceability of the food supply chain, for example biomarkers to certify the origin of meat products. In addition to the value of this authentication in combatting fraud, there will be benefits in reducing waste. However, improved quality control does not depend on technological advance alone: there must also be better communication between national and international regulators, producers and retailers, and better engagement to inform the public-at-large.

The IANAS report discussed two other strategies for reducing waste of perishable food: adding value by its use as raw material for processing into other products and donating surplus food to food banks for distribution among vulnerable populations. Food banks, as part of food safety-nets[15], can be seen as a practical response to the retail problem of food waste since they focus on access and use of what has been produced and commercialised, but these are not without challenges. Food banks may not necessarily provide balanced food options, since they depend on what is going for waste at a particular time, and they may act as a disincentive for local enterprise and traders.

---

[13] Analysis of variation in food waste between countries is discussed in detail: see http://www.fao.org/platform-food-loss-waste/en/.
[14] http://foodsustainability.eiu.com/.
[15] Meta-analysis of published evidence on social protection interventions (particularly social assistance programmes) identifies meaningful impact of safety nets on both quantity and quality of food consumed by beneficiaries while there is virtually no evidence to support claims that such programmes create 'dependency' (Hidrobo *et al*., 2018).

The NASAC report discussed low-cost solutions to preserving food to reduce waste, which may have significant ramifications. For example, to prevent weevil larvae, a storage pest of cowpeas, an approach has been successfully licensed and disseminated in developing countries[16] and this specific innovation has encouraged further private investment in other innovative storage solutions for smallholders (see Lowenberg-DeBoer and Musa, 2017). Also, thermal processing has been widely employed in the food industry for extending product shelf-life by inhibiting or inactivating micro-organisms but uptake of these technologies has been delayed in parts of Africa by low rates of electrification. Investment in solar power now underpins new opportunities in thermal processing (see also Chapter 6 for work on smart villages). Such ideas offer enterprise and employment opportunities for landless people in particular and could facilitate employment prospects for women and young people.

3.5 Food processing

There are opportunities for using science and engineering advances in food processing to reduce food waste in the steps after production. There are also many other opportunities to use food processing, to widen food distribution, fortify staple foods, extend seasonal availability and shelf-life, develop healthy foods and enable easier meal preparation to satisfy consumer demands (for example, Teng *et al*. (2015) in discussing technology opportunities in Asia).

Market research data from Euromonitor[17] show that the balance in food sold has shifted from fresh to packaged food in many developed countries. For example, the UK eats almost four times as much packaged food as fresh produce. Increasing consumption of processed food has raised considerable health concerns associated with reduced nutrients and added salt, sugar and fat content. However, there are opportunities for reformulation to produce healthier products. As discussed by AASSA, the food processing industry is highly adaptable and could introduce healthy manufactured foods into the food chain. There may need to be incentives for manufactured foods that offer the same high palatability and price appeal but minimise inclusion of unhealthy ingredients (e.g. trans fatty acids and highly available sugars and starches) and are produced to have health attributes (see Chapter 4 for further discussion).

These opportunities and challenges for food processing occur worldwide. NASAC discussed how modernisation of smallholder farming and its integration into fast-growing agri-business chains can produce quality food products that meet rapidly evolving urban demand, particularly with regard to enhanced quality, convenience and safety. But meeting this changing consumer demand requires substantial private sector investment. The introduction of a new processing technology does not necessarily imply a more heavily processed food, in the sense of a more degraded food. As discussed by AASSA, many innovative technologies, for example high-pressure processing, are designed to retain the natural characteristics of food: better scientific understanding of the relationships between food structures, nutrition and health (Chapter 4) can lead to new food processing approaches to ensure retention of nutrients and food structures. Moreover, there are many opportunities to improve packaging: current non-biodegradable materials (e.g. plastic) present a disconnect with environmental objectives and research needs to be conducted on the production and use of smart biodegradable materials that will prolong food shelf-life, quality and safety.

There is significant interest in promoting cohesion between food science, engineering and technology, and nutrition; yet, until recently, skills in food science and technology were at risk of being marginalised. However, work to follow up the Global Visions report from the International Academy of Food Science and Technology[18] indicates that the status of food science, engineering and technology is starting to increase in importance in national food and health strategies. The skills of food science and technology are essential for addressing several of the SDGs, for example in adapting to new raw materials to decrease the burden on the climate. New varieties of crops may require a higher flexibility of production chains. Limitations in other resources will require new processing techniques, with less consumption of water and energy and a recycling approach that can make use of side-streams of the food industry and thus reduce waste.

3.6 Understanding global markets and addressing their volatility

International trade can contribute to reducing food insecurity but the magnitude of this role remains a subject of long-standing and intense debate (e.g. IFPRI, 2017b), in particular between those who propose food self-sufficiency – accepting import restrictions to support local production – and those who propose the removal of barriers to trade. The regional reports tended to emphasise different aspects of markets and trade. For example, NASAC discussed smallholder-market issues and AASSA addressed intra-regional trade issues (for reducing tariff and non-tariff barriers to trade, and formation of cooperative free trade agreements), whereas EASAC and IANAS covered global trade flows.

[16] https://picsnetwork.org/.
[17] www.euromonitor.com.
[18] https://www.ifst.org/about-policy/ifst-contribution-iufost-global-visions-report.

IANAS also discussed unintended consequences of trade agreements on producers, for example small-scale maize producers in Mexico who could not compete with US maize producers when agricultural trade between the two countries was liberalised.

As discussed in the IANAS and EASAC reports, worldwide projections show that the geographical divergence between production and consumption will increase. Accordingly, international trade will become increasingly important as a mechanism to balance needs and availability. Trade in agricultural products has historically been distorted by subsidies and barriers to market access. Some of these defensive barriers further damaged food security in importing countries by amplifying price increases and their volatility. But as IANAS highlighted, stability in the price of food in a globalised market is a public good that requires a cooperative approach on the part of all countries. IFPRI (2017b) confirmed advice that the international community should promote a global trading system on the basis of efficient and transparent markets, respecting World Trade Organization (WTO) rules appertaining to international public goods and acting to eliminate trade distortions. Recent research shows that international food trade is important for micronutrient access (Wood *et al*., 2018a). However, it is also important to appreciate that smaller countries have relied on trade barriers to protect local agricultural production: further research is required to provide the evidence to clarify options in developing trade policy.

Analysis of vulnerabilities in key regions, for example the Middle East, Central America and sub-Saharan Africa (d'Amour *et al*., 2016), indicates that a region-specific combination of national increases in agricultural productivity and diversification of trade partners and diets can decrease future food security risks. Devising and operating global and regional systems requires a better evidence base. What then are the data collection and research priorities associated with achieving these objectives?

The EU-Africa research and innovation roadmap (EU-Africa High Level Policy dialogue on Science, Technology and Innovation, 2016) discusses research priorities associated with a set of linked objectives:

- Understanding non-tariff trade barriers, for example clarifying differences in perception about food quality and safety attributes. In its work, EASAC also explored the research agenda associated with ascertaining ‘what is fair trade?’, for example assessment of product labelling and regulatory policies as trade barriers. There is need to distinguish between trade restrictions governed, for example, by environmental considerations and labour standards and those that are politically motivated.

- Collaborating in development and widespread application of methodologies for food safety issues and standardisation of traceability to permit trade in food products.

- Explaining international price volatility in markets to build system resilience to the benefit of both consumers and agribusinesses. EASAC discussed the research issues for examining linkages between extreme events and price volatility, and the potential role of regulatory policy instruments in commodity markets in price transmission between global markets and local food systems. Research priorities for analysing price volatility and its implications on food systems are discussed in detail by Kalkuhl *et al*. (2016). There is also continuing need for research to ascertain the correlation between individual and local risks to understand aggregate and global risks to the system (Cosstick, 2017).

- Promoting new mechanisms in global value chains, for example linking smallholder farms to markets, and adding value in responding to market opportunities by food processing and labelling.

The EASAC report reviewed evidence relating to the controversy of whether, and if so when, increasing trade flows provoke price instability or whether they promote market resilience. The analysis of food prices is further complicated by potential volatility spill over from oil markets and the implications of competition for land use for food crops and bioenergy (see also Chapter 6). Thus, according to the EASAC recommendations, the broader research agenda for markets should capitalise on new modelling and analysis (see also next section), gather evidence about how market shocks occur and propagate, and what effects are likely to evolve as a result. One aspect in understanding global markets, not assessed in detail but alluded to in the regional work, is the need to evaluate the economic, environmental and social effects of foreign direct investment in land and other production assets (see also Chapter 6). Within the food systems context, there is also need for research to do more to understand the economics of agricultural production as part of assessing global market architecture and dynamics, for example the impact of subsidising commodities that may act to promote consumption of obesogenic diets.

3.7 Connections with basic science, digitisation and big data

Attempts to manage complex food systems have implications for interdisciplinary and participatory research agendas. Historically, research studies on agriculture, nutrition and public health have not been designed to tackle problems that span environmental change, food system interrelationships and health outcomes (Dangour *et al*., 2017). Planning for sustainable, equitable and healthy food systems requires integration of methods from different scientific disciplines, including the social sciences, to understand consumer values, new analytical approaches and intersectoral policy analysis. It also requires recognition that progress crucially depends on effort in the basic sciences, for example biology, chemistry, social sciences, mathematics and engineering, to provide the knowledge to serve as the foundation for all other endeavour.

The term 'big data' describes the use of techniques to capture, process, analyse and visualise potentially large data sets in a reasonable timeframe. The possibility of a disruptive data revolution in agriculture and food chains, stimulated by the rapid advance of digital and block-chain technologies, is discussed in detail in the EASAC report. All of the IAP regional reports exemplify opportunities to build and analyse multi-sectoral big data platforms. If these opportunities are to be realised, there is much to be done to fill data gaps, to agree improved procedures for data collection, analysis and sharing, while also resolving data ownership and privacy concerns.

There are also important issues to settle for data validation and verification, for the use of common standards, algorithms and protocols to enable data analysis and linking, especially from disparate sources (Burke and Lovell, 2017; Jean *et al*., 2016), and for privacy requirements in sharing and using data. There is a further dimension in cloud computing that allows for crowd sourcing and active participation by citizens for mutual accountability and the provision of highly disaggregated geo-reference data that may begin to play an important role, for example in monitoring climate change and disease patterns and informing early warning systems. Communication science additionally offers ways to improve systems to share knowledge at all levels. In this and other contexts, it is worth noting that as the private sector is increasingly active in collecting big data, it becomes ever more important to identify mechanisms to ensure public sector access to critical information. Subject to progress in resolving issues for standardisation and sharing, there are significant opportunities for cross-sectoral analysis using different databases. Big data may also become a useful tool with which to measure and audit the societal impacts of science.

As reviewed by NASAC, the potential of big data to reveal patterns, trends and associations will be highly useful in major tasks such as progressing the SDGs. There are also many specific tasks that will also be facilitated, for example risk detection, logistic programme planning, price comparisons, predicting diseases and improving health management systems. For example, in other analysis of Africa, a dataset covering land use and production data of more than 13,000 smallholder farm households in 17 countries demonstrates the importance of targeting poverty through improved market access and off-farm opportunities (Frelat *et al*., 2016): '*big datasets can be used to identify generic patterns that can be used to prioritize policies, despite the huge diversity in smallholder farming systems …*'

Further examples from the NASAC and other reports will be discussed in Chapter 5 for precision agriculture. One other example will be included here as relevant to the previous discussion on markets and volatility. The EASAC report draws attention to the importance of improving data collection on agricultural commodity trade flows and prices, accompanied by modelling of databases to inform global governance and risk management. The Agricultural Market Information System[19] was established at the request of the G20 agriculture ministers, and the World Bank and others are also now creating early warning systems, based on improved modelling, to render markets more predictable.

[19] www.amis-outlook.org.

4 Transforming diets for nutrition outcomes and public health

'*The nutritional and health sciences have major roles to play in defining healthy diets, and the behavioural and social sciences have major roles in enabling better understanding of motivating factors for consuming healthy diets.*' AASSA

As discussed in Chapter 1 (and Appendix 2), the work of FAO, WHO, IFPRI and others has described how tackling nutrition is central to achieving the SDGs and other societal priorities but warns that the world is not currently on track to reach agreed global targets. Increasing healthcare costs in many countries associated with poor diets will probably trigger further interventions to shift dietary preferences.

In transforming diets, there is much more to be done to assess the impact of current policy and programmes (Haddad, 2015), including: evaluating the relative impacts of strategic initiatives in different countries; understanding the critical issues for designing policy options; monitoring the return on investment for different actions; and clarifying the intersection with other societal priorities, in particular climate change. As emphasised in the recent report of the CFS High Level Panel of Experts on Food Security and Nutrition (CFS HLPE, (2017)), there are multiple needs to satisfy in pursuit of nutrition targets and these include strengthening the integration of nutrition in national policies; strengthening global cooperation; addressing nutritional vulnerabilities of particular groups; recognising and addressing conflicts of interest; and improving data collection and knowledge-sharing.

There is a significant research agenda associated with developing and implementing the opportunities to transform diets for nutritional outcomes and public health (for example, Haddad *et al*. (2016) and other sources in Appendix 2). The present chapter draws on some of the specific topics reviewed in the four regional reports, to highlight global priorities, with particular reference to the need to support fundamental science and use its outputs to drive innovation.

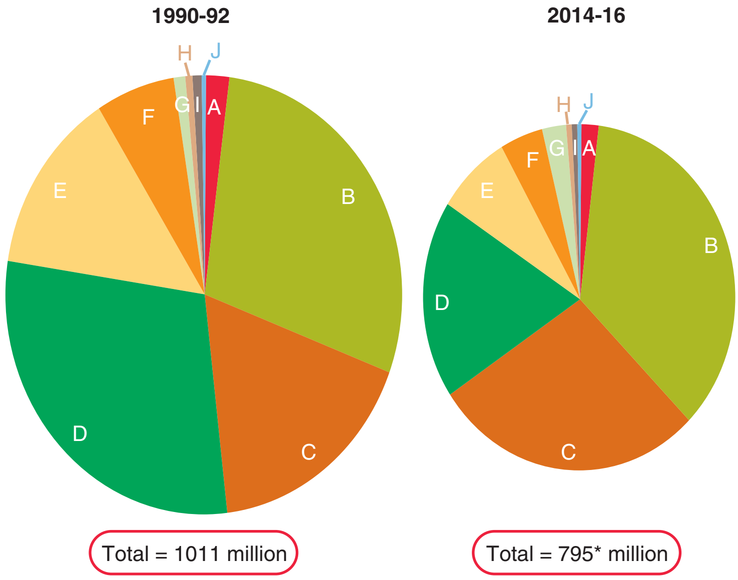
4.1 Issues related to malnutrition and defining healthy and sustainable diets

All four regional reports cover the spectrum of malnutrition, encompassing undernutrition, micronutrient deficiencies, and overweight and obesity. The regional reports also discuss the relevant demographic changes, in particular population growth and ageing (including ageing in the farming and agricultural sciences sectors). There are, of course, major differences in the incidence of undernutrition and micronutrient deficiencies within and between regions, particularly in parts of Africa, Asia and the Caribbean compared with the rest of those regions, as documented in detail by NASAC, AASSA and IANAS. There are also significant differences in the rate of progress: see Figures 3 and 4 (which do not take into account the deterioration within the past year in certain respects, see Chapter 1).

In country-by-country assessment of progress on health-related SDGs (GBD 2016 SDG Collaboration, 2017), three indicators were selected for monitoring SDG2 (zero hunger): child stunting, child wasting and child overweight. Detailed analysis is provided in this reference on current performance on these indicators and projected attainments in 2030, and we will not repeat this analysis here (but see the next section for child overweight implications).

As emphasised by NASAC and discussed in all the reports, for too long food security policy, and monitoring and evaluation at national, regional and global levels, has focused on the supply of staple grains. This focus must be broadened to include the year-round supply of other foods essential to meet nutrient requirements. Achieving this goal requires the transformation of food systems with comprehensive nutrition policies (Malabo Montpellier Panel, 2017) – to increase the nutritional value of foods at affordable prices, sustainable for livelihoods and the environment – with multiple benefits for the consumer and producer. EASAC remarked that nutrition policy lags behind nutrition science. The high value of improved nutrition to societies should be supported by policy alignments to create compatibility between nutrition, consumer health and economic goals for farmers and food processors.

In planning for FNS, it is a prerequisite to be able to define what are healthy diets. However, perceptions of what is a healthy diet are changing. There is now an emphasis that a healthy diet also has to be sustainable, that nutrient requirement will change over the lifespan and that the impact depends on the individual (e.g. because of influences of immune system and genetic variability). Views on the evidence for components of healthy diets have changed; for example, recent publications have examined the role of carbohydrates and fats in cardiovascular disease risk, sometimes with conflicting interpretations of evidence (Dehghan *et al*., 2017). As discussed by AASSA, accumulating knowledge on the nutritional and other effects of food will progressively help to clarify what is meant by the term 'healthy diets'. However, global improvements are required to the methods used to evaluate and synthesise diverse evidence and grade recommendations in dietary guidelines (Bero, 2017). There is also need to pay attention to concerns expressed (Bero, 2017) that there



	Number (millions) 1990-92	Number (millions) 2014-16	Regional share (%) 1990-92	Regional share (%) 2014-16
A Developed regions	20	15	2.0	1.8
B Southern Asia	291	281	28.8	35.4
C Sub-Saharan Africa	176	220	17.4	27.7
D Eastern Asia	295	145	29.2	18.3
E South-Eastern Asia	138	61	13.6	7.6
F Latin America and the Caribbean	66	34	6.5	4.3
G Western Asia	8	19	0.8	2.4
H Northern Africa	6	4	0.6	0.5
I Caucasus and Central Asia	10	6	0.9	0.7
J Oceania	1	1	0.1	0.2
Total	**1011**	**795***	**100**	**100**

Figure 3 The numbers and share of undernourished people by region, 1990–1992 and 2014–2016. (Source: FAO, The State of Food Insecurity in the World: http://www.fao.org/3/a-i4646e.pdf.)

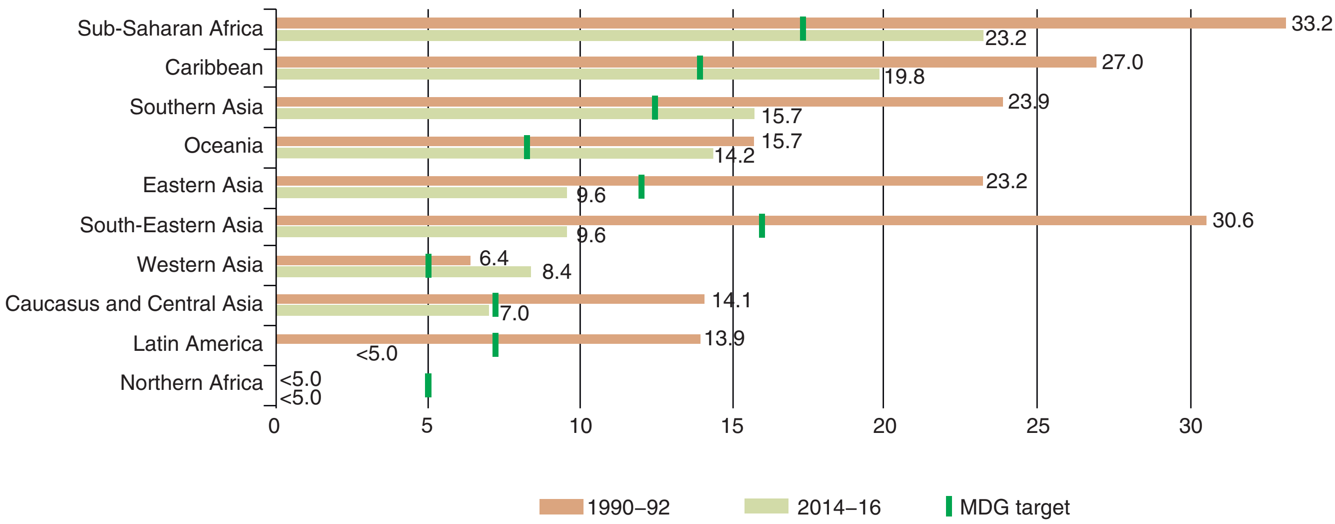


Figure 4 Undernourishment trends: progress made in all regions, but at very different rates. MDG, Millennium Development Goal. (Source: FAO, The State of Food Insecurity in the World: http://www.fao.org/3/a-i4646e.pdf.)

may be bias in the research agenda associated with the interests of those financing research on dietary impacts.

Future dietary recommendations will also need to take account of societal values in relation to diverse factors such as animal welfare, land use, ethics, cultural preferences and perception of risks associated with new technologies. Planning for FNS will require a wide range of culturally acceptable food types to be made available—and this has implications for farming. In addition to being healthy and culturally acceptable, it is now also critically important for a diet to be environmentally sustainable, as discussed subsequently. However, as AASSA cautioned, it is also challenging to define what a sustainable diet translates to in practice.

Measurement of sustainable farming systems and diets requires evidence-based metrics.

The urgent challenges for improving FNS were introduced in Chapter 1. All four regional reports discuss in detail the specific problems of undernutrition and micronutrient deficiencies and the approaches to tackling these problems, including, for example, biofortification and removal of anti-nutrient compounds such as phytates and oxalates. The evidence base for combatting undernutrition and micronutrient deficiencies is relatively well-established (see, for example, Appendix 2 and Figures 3 and 4) and familiar to policy-makers. There is less evidence available on the determinants of overweight and obesity and on how to

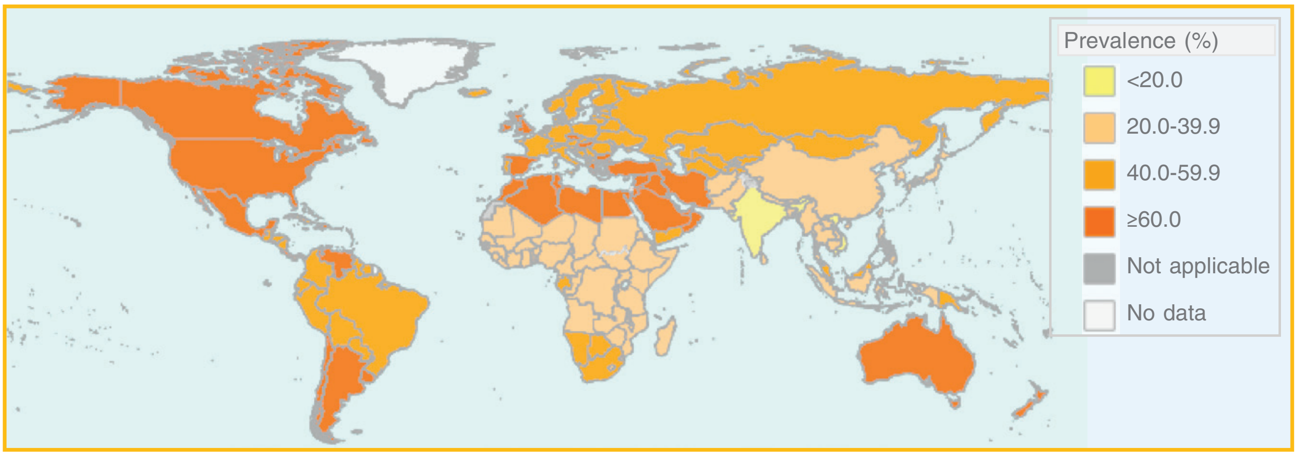


Figure 5 Prevalence of overweight among adults ages 18 + (2016). (Source: WHO Global Health Observatory on Overweight and Obesity: http://www.who.int/gho/ncd/risk_factors/overweight/en/.)

tackle these conditions and provide optimal age-related nutrition.

4.2 Overweight and obesity

Overweight and obesity are the result of an excessive intake of food or an unbalanced dietary intake, in particular the consumption of too much energy from food (and lack of sufficient physical exercise), without necessarily having an adequate intake of all other nutrients. Over-consumption of energy is a complex phenomenon and is discussed in further detail in the reports of AASSA and EASAC, in particular. NASAC noted that excess weight gain can be a consequence of poverty and other forms of deprivation. The evidence discussed by IANAS from several countries of the Americas shows that a reduction in poverty and undernutrition over the past 10 years has been associated with an increase in obesity. Thus, poverty reduction is a necessary but not sufficient condition for adequate and healthy diets. Detailed data on the prevalence of overweight and obesity are published by WHO (see, for example, Figure 5).

Some research suggests that the incidence of obesity is related to the wide availability of processed foods, although other research finds less association between processed food consumption and body weight (for example the UK cross-sectional study (Adams and White, 2015)). There is need for longitudinal research to examine these associations further. Foods rich in simple sugars and easily digestible carbohydrates are frequently cheaper than other foods, making the poor especially vulnerable. For example, research on trends in the affordability of sugar-sweetened beverages (over the period 1990–2016, data from 82 countries) concluded that the affordability increased more rapidly in low- to middle-income countries (Blecher *et al*., 2017). EASAC recommended that the perverse price incentives to consume high-calorie diets should be removed and new incentives for healthy nutrition introduced. More research is warranted, to examine the responses of food systems to the increase in household incomes, to understand consumer behaviour and how to influence consumption, so as to increase demand for nutritious foods. However, as discussed elsewhere (Anon., 2017b), to instigate long-term change, systems cannot afford to project the responsibility onto the individual; governments must incentivise corporations to market food that is consistent with a healthy and sustainable diet[20]. As the primary goals of the food industry (maximising shareholder value) and public health (maximising health and minimising health inequality) are often poorly aligned, more must be done to ensure that the food industry holds health as a core value (Cosstick, 2017).

It is a particular concern that fewer than 5% of countries worldwide are projected to achieve targets for childhood overweight (GBD 2016 SDG Collaborators, 2017), in view of the propensity for obesity to continue into adulthood. As noted by AASSA and IANAS, onset of overweight in childhood is likely to create long-term problems for health, unless its management is improved. Health behaviour is shaped by the obesogenic environment but better evidence is required on what interventions to prevent and reverse overweight will work and what is particularly relevant to children and to adults. Furthermore, standard tools for measuring

[20] For example, a recent WHO Europe policy briefing 'Incentives and disincentives for reducing sugar in manufactured foods' (http://www.euro.who.int/__data/assets/pdf_file/0004/355972/Sugar_Report_eng.pdf), based on food supply chain analysis, identifies how governments can devise sugar reduction strategies by incentives/disincentives for manufactured foods and retailing. Further discussion of various policy interventions (e.g. taxes, subsidies, trade agreements) to improve diet is provided in the comprehensive literature review of Hyseni *et al*. (2017).

overweight (body mass index) do not necessarily reflect the risk for NCDs, particularly in children, and the research agenda should include the search for new indicators for disease risk. Micronutrient deficiencies during pregnancy may have a strong impact on NCDs in later life (Gernand *et al*., 2016), possibly through an effect on the epigenome: thus, it will be necessary to take account of micronutrient as well as energy intakes. Furthermore, personalised medicine and personalised nutrition potentially open up opportunities to overcome the limitations of excessively generalised recommendations.

4.3 Variation in population sub-groups

When considering issues for the provision of a healthy diet to address the complete spectrum of malnutrition, modelling nutrition and food supply at a national level may provide a valid starting point but there are often large local variations and the needs of specific population subsets must also be clarified. There are particular issues for vulnerable groups such as children (where a healthy, diversified diet is especially important for the first 1,000 days from conception, including for cognitive development that will be the basis for future behaviour) and for the mother during pregnancy, the elderly, patients and migrants. As discussed by EASAC, consideration of these vulnerable groups requires cross-disciplinary research for better understanding of nutritional needs together with systematic, longitudinal data collection to generate robust evidence on the extent of malnutrition in vulnerable groups. These impacts are often poorly quantified, the information currently available is often outdated and, in consequence, attempts to combat malnutrition in vulnerable groups are often not strongly evidence-based.

Further information is discussed in the regional reports: one group will be highlighted here, the elderly[21]. The ageing of many populations, most imminently in some Asian and European countries, has important implications for future dietary needs in these countries. Older people may require more energy-dense diets (because of reduced appetite) and greater amounts of higher-quality dietary proteins to attenuate the effects of body muscle loss with ageing, related to impaired health and physical performance in general[22].

Information on other demographic changes is also discussed further in the regional reports: one group will be highlighted here, the middle class. An expanding middle class in most countries is bringing an increased demand for higher-value foods such as meat, dairy, eggs, fish, nuts and fruit. According to CFS HLPE data, three-quarters of the global population currently derive most of their daily protein from plants but, on the basis of the trends in increasing income, it is predicted that demand for global meat and milk production will continue to increase. At the same time, nutritional transitions associated with other demographic changes, such as urbanisation, will lead to increasing demands for processed foods (see Chapter 3). AASSA and NASAC discussed the consequences for replacing locally grown foods (often coarse grains) by processed foods that are more calorie dense and a risk factor for overweight and obesity.

4.4 Exploring health co-benefits of climate change mitigation by changing diet

Issues for climate change impacts on agriculture and food systems were introduced in Chapter 3 and are further discussed in Chapter 5. There may also be, however, considerable opportunities to mitigate the contribution of food systems to greenhouse gas (GHG) production and climate change by reducing over-consumption of food and by changing specific dietary habits. However, while there is an accumulating evidence base on the impacts of agriculture on GHG emissions, implications for adjusting diets are more contentious.

A systematic review (Aleksandrowicz *et al*., 2016) of the evidence on changes in GHG emissions and land and water use achieved by shifting current Western dietary intakes to environmentally sustainable dietary patterns demonstrated that reductions in environmental footprint were generally proportional to the magnitude of animal-based food restriction. These dietary shifts also yielded modest benefits in all-cause mortality risk. Trends in ruminant meat consumption in different regions were published recently as part of the set of indicators for monitoring climate change and its mitigation (Watts *et al*., 2017). Comprehensive analysis of epidemiological evidence (Etemadi *et al*., 2017) has shown that the risk of all-cause mortality is associated with red but not white meat. However, the published literature on specific health effects of red meat consumption, for example on colorectal cancer, has sometimes been conflicting (for example, Lin *et al*., 2004; Alexander and Cushing, 2011) and distinction needs to be made between red meat and cured red meat.

The issues associated with shifting diets, in particular meat consumption, are discussed in detail in the

[21] Globally, the population is ageing rapidly. Between 2015 and 2050, the proportion of the world's population over 60 years is estimated nearly to double, from 12% to 22%: http://www.who.int/mediacentre/factsheets/fs381/en/.
[22] There are also particular issues for diet and cognitive function in older age, and research gaps have been discussed in detail in the literature (e.g. Vauzour *et al*., 2017). More generally, there are opportunities to target new food product development with functional health benefits designed to address the needs of older consumers (see Baugreet *et al*., 2017).

Chatham House report (Wellesley *et al*., 2015). Other research on the co-benefits to health of mitigating climate change by altering diet, particularly in Europe, is discussed in the EASAC report. A recent study in India (Vetter *et al*., 2017) comparing GHG emissions of major crops and livestock provides further support for the possibility that change in diet and agricultural production decisions could have a significant effect on GHG emissions. It is important to do more to collect evidence on these co-benefits, and any unintended consequences, as one indicator of the societal impacts of climate change and its mitigation.

Levying GHG taxes on certain food commodities could be a health-promoting climate policy in many countries (Springmann *et al*., 2017). Sparing food groups known to be beneficial for health from taxation and using a portion of tax revenues for health promotion could aid vulnerable groups while still attaining the general changes towards diets that are more environmentally sustainable. Proposed tax schemes (for example, on red meat) are discussed further in the EASAC report but the assessment of macroeconomic and other consequences is challenging. Further research is also needed to clarify other implications of dietary shifts and the potential trade-offs with regard to climate change mitigation and natural resources (for example, water use (Muller and Schafer, 2017)).

AASSA noted that narratives requiring changes to farming systems (e.g. reducing animal production) are often overly simplistic and one-dimensional. It is important that all interactive elements of food systems are assessed, that investigation is evidence-based, that evidence is applied in the correct context and that conclusions are re-assessed if new evidence is forthcoming (e.g. if improvements in animal feed efficiency were to be obtained, (Mottet *et al*., 2017)). In deriving conclusions about the future of animal production, in addition to GHG emissions and biological efficiency of production, considerations such as type of animal, health/nutrient characteristics of animal-based food, other products from animals (in particular, hair, wool, leather, draught power, manure and transport) and alternative land use are all important. For example, recent analysis of dairy products in terms of four domains of sustainability – for nutrition, economics, society and the environment – concludes that trade-offs need to be made between nutrient density and environmental constraints (Drewnowski, 2017). Sustainable diets are the outcome of sustainable food systems and will vary from country to country.

The regional reports adopted varying perspectives on what a sustainable diet might be. For example, evidence reviewed by AASSA showed that the efficiency of animal production is dependent upon competitive land use (large areas of grazing land may not be suitable for other agricultural use). Foods of animal origin are of high protein quality and provide relatively large amounts of essential minerals and vitamins which, along with their organoleptic qualities, helps to explain why consumers demand such products as their income increases. These foods are essential in addressing nutrient deficiencies among children because of the nutrient density of these foods: there may be a particular concern of increasing iron deficiency if lowering meat intake in some groups, because of the lower bioavailability of iron from other sources. The AASSA report also noted that there have been recent advances in methods for describing protein quality that may lead to readjustment of assumptions about the current status of nutrition security in some countries and that this readjustment may have implications for dietary recommendations (Rutherfurd *et al*., 2012).

As EASAC concluded, more effort is required to clarify the extent to which there is a disconnect between achieving COP 21 objectives in terms of reducing animal product consumption to mitigate climate change and the advice for consuming a healthy diet commensurate with targets embedded in the SDGs. At the same time, research and development opportunities for meat substitutes as innovative food are worth pursuing (Dance, 2017).

4.5 Food structure and content

Traditionally, the study of human nutrition has relied upon a reductionist approach, whereby a diet is seen as a combination of meals, meals as a combination of foods, and foods as a combination of nutrients. AASSA cited evidence to query this paradigm, noting that the complex physical and chemical structures of food influence the gut environment and, hence, the extent and rate of nutrient digestion (Kongerslev Thorning *et al*., 2017). This has significant implications for the metabolic response and, therefore, potentially for the healthiness of the diet. Additional assessment of the food–gut microbiome relationship is provided subsequently. Furthermore, foods contain many compounds not classically viewed as nutrients, for example phytochemicals, bioactive proteins and peptides, probiotics and plant fibre, and these components may have significant positive effects on human health (see further discussion subsequently). Moreover, anti-nutritional factors present in many foods may have negative influences on the consumer: for example, trypsin inhibitors in legumes, tannins in legumes and cereals, and phytate in cereals, which may affect protein quality and bioavailability. Phytates can also affect the bioavailability of iron and zinc from cereals. New opportunities are coming within range to tackle anti-nutritional factors, for example genetic improvement of beans with reduced tannin content.

Scientific advances in understanding these additional dimensions are driving a reconsideration of the nature and properties of individual foods and the implications for dietary responsiveness and health outcomes. AASSA postulated that knowledge of the holistic properties of foods and how they interact with the properties of other foods will be important factors in understanding and defining healthy diets. This research also holds significant promise for improving the quality of the food system and the foods it offers to consumers. The private sector needs to become an active part of making the food system more nutritious and the food environment healthier.

4.6 Food safety

An important aspect of FNS is food safety—food free of harmful micro-organisms and toxins, free from adulteration or other contamination. Food allergies also need to be accounted for, raising additional issues for labelling, traceability and integrity of the food system.

All countries have regulations and standards that products must meet before retail. However, as observed by NASAC, implementation is often constrained by lack of capacity to reach the many small to medium scale producers, and by lack of capacity to enforce regulations. Testing is often expensive and lack of it may limit the distribution and export of foods. Nonetheless, many innovative approaches to testing are now being adopted. Particular issues for food safety are exemplified in the regional reports: among the greatest problems are those discussed in the following three sections.

4.6.1 Micro-organisms

Food-borne diseases are prevalent, for example as discussed by IANAS. Industrial-scale food production and long transport networks can contribute to serious food-borne disease outbreaks, as described in further detail by IANAS and EASAC.

Antibiotic-resistant bacteria in food-producing animals may contribute to increased infection in patients and the threat of antimicrobial resistance is a global problem. The EASAC report discussed the problems associated with excessive use of antibiotics in agriculture and the lessons of good practice in reducing farm use of those antibiotics that are most relevant for human healthcare. Antibiotic-resistant bacteria or resistance-encoding genes may transfer from animals to humans through the environment, the food chain or by direct contact. In some countries, as much as 80% of total use of antimicrobials is in the animal sector and emerging economies are projected to increase their use in livestock (Holmes *et al*., 2018). There is considerable use in some countries as growth promoters. Reforms recommended in WHO 2017 guidelines (Holmes *et al*., 2018) include discontinuation of routine use of antimicrobials for growth promotion and disease prevention in healthy animals, and actions to help preserve the effectiveness of those antimicrobials that are critical for human medicine. There is need to understand better the impact of antibiotics and resistance genes on ecological systems to develop environmental mitigation strategies (Asaduzzaman, 2018). Breeding for improved disease resistance (Chapter 5) also has to be part of the solution to limit antibiotics on the farm and improve both animal and human health.

4.6.2 Mycotoxins

Pests and diseases may lead to the accumulation of mycotoxins, which are secondary metabolites produced by fungi with potentially severe health consequences. Contamination of food with mycotoxins can also occur after harvesting, mainly because of improper or unhygienic practices during storage, processing or transportation. According to NASAC, mycotoxins are reported to be widespread in major African food categories, in particular maize and groundnut products, spices and in livestock products. Safety regulations are more often applied for export goods than for the domestic market and this is of particular concern in smallholder agricultural settings where farmers produce and store a large proportion of the food they consume and where conventional food surveillance mechanisms are not applied. More epidemiological research is needed to establish patterns of contamination and the health impacts. Research and innovation are also needed to develop cheaper testing methods and cost-sharing practices. The analytical challenges are particularly acute in field conditions where resources, including electricity, are very limited. Among the solutions that NASAC describes are those offered by the World Food Programme portable testing kit and the Lab-on-Mobile-Device platform (Shepherd and Gelderblom, 2014). Research and innovation are also already contributing in other ways: for example, in proof-of-principle for a biotechnology strategy for generating peanuts that are nearly immune to aflatoxin contamination (Sharma *et al*., 2018).

The problem of mycotoxins and other toxins is worldwide. EASAC discussed how marine toxins are increasing because of climate effects on algal bloom formation and migration of potentially contaminated species (see also Watts *et al*., 2017), which brings new challenges for food monitoring and for research to understand the mechanisms involved.

4.6.3 Other contaminants

The regional reports describe other important contaminants such as persistent organic pollutants and heavy metals. Continuing research is needed on the impact of chemical contaminants (and their combinations), whether accumulated from the environment, during processing and distribution, or by penetration from packaging materials, to assess toxicology, estimate human exposure and calculate tolerable daily intake. Many low-paid (often female) labourers are exposed to various harmful substances in a range of production systems. Of particular concern is the over-use of fertilisers, pesticides and herbicides in production systems that affect human health and leach into the environment, affecting not only the area where they are used but also downstream systems and the environment in general (see, for example, Cimino *et al*., 2017).

As discussed by EASAC, the ongoing activities to minimise long-standing threats to food safety should be synchronised with risk assessment and management of newer threats and consumer concerns, such as food additives, growth promoting hormones and new technologies to process food. Authentication measures are also increasingly needed, to document the integrity of the food supply chain and prevent adulteration. A range of analytical tests can be applied to measure natural or synthetic contaminants but there are continuing diagnostic challenges, for example to identify the use of synthetic steroids and growth promoters that may not be detectable by conventional methods. A more comprehensive approach to testing requires better communication between national and regional regulatory authorities, producers and retailers, and renewed commitment to academia-industry collaboration to develop sensitive point-of-production and on-site rapid monitoring. It is also worth emphasising that food safety may become a greater problem if the increasing trends to adopting special diets continue. For example, gluten-free products may contain higher levels of arsenic, cadmium, lead and mercury, as documented recently (Wunsche *et al*., 2018).

4.7 Innovation in nutrition and capitalising on work at the scientific frontiers

There are many examples in the regional reports of innovative foods, innovative diets and innovative systems of provision. The disparate examples discussed in the following sections were chosen because of their global applicability and to illustrate the point that continuing research is vital to ensure that full use is made of the scientific opportunity. It is also worth re-emphasising that digitisation in collecting and monitoring food intake and nutrition data contributes significantly to the potential opportunities for using big data. Robust data collection to map health and nutrition indicators across regions will become a valuable tool with which to target resources, develop policies and track accountability (Annan, 2018).

4.7.1 Orphan crops and functional foods

Exploiting the nutritional properties of underutilised, indigenous crops holds potential for diversifying food systems more widely. IANAS described in detail numerous species used ancestrally by local communities which present high potential for food production. The use of such crops in agriculture will be described further in Chapter 5 and it is noteworthy that traditional crops may have other useful properties. NASAC described *Amaranthus* (Singh and Singh, 2011), used as a vegetable in many traditional African recipes; but the grain also has singular gelatinisation and freeze/thaw characteristics that can be utilised in other food products as stabilisers and thickeners, as well as in non-food applications such as biodegradable films and paper coatings. Another example is sorghum, a gluten-free cereal that contains various phenolic compounds, plant sterols and policosanols that may have diverse health benefits and satiety-promoting activity (Taylor and Anyango, 2011).

Other functional foods, for example oily fish supplying omega-3 fatty acids, are recognised as valuable worldwide and this theme was developed further by AASSA with the example of the FOSHU (foods for specified health uses) movement in Japan. There is likely to be further scope for capturing and promoting indigenous knowledge. Research is needed to explore the health properties of such foods and to inform how food technology can be used to develop new functional foods – developed specifically to promote health or reduce the risk of disease – as part of healthy sustainable diets.

4.7.2 Consumer behaviour

There is considerable interest in using advances from research in the social sciences to understand and inform consumer dietary choices and consumer action to reduce household food waste (Romani *et al*., 2018). EASAC discussed how social practice theories are now bringing new perspectives to food consumption studies because they allow for a consideration of drivers and barriers to help analyse habitual behaviour in everyday life (see, for example, Sahakian, 2015), although there is less understanding about the complex cumulative effects of social learning and social mimicking processes. More research is warranted to clarify the drivers of demand and how to change behaviour, including the acceptance of innovative foods and innovative diets, and to examine public understanding of the environmental implications of food choices (Macdiarmid *et al*., 2016). As discussed previously (section 3.6), research is also needed to understand impacts of business models, for example agricultural commodity subsidies, on consumption and health.

4.7.3 Microbiota

All regional reports remarked on the importance of recent advances in gut microbiome science. Research has demonstrated that the gut microbiome performs important biochemical functions for the host, and disorders of the microbiome are associated with diverse human diseases. For example, there is emerging evidence for a gut–brain axis (Mayer *et al.* 2015).

Recent progress in genome sequencing technologies enable investigation of the complex gut microbiome at both genetic and functional levels, mapping variability between individuals and between populations (Qin *et al* 2010). Integrated with studies on diets (for example, in Africa appertaining to a wide range of herbal, medicinal and fermented products from indigenous foods), the research advances are beginning to reveal how food and the microbiome interact and what may be the consequences. The gut microbiome is an important factor that seems to contribute to obesity by altering energy harvest and storage in the host (Viciani, 2017). It is becoming clearer (Byndloss and Baumier, 2018) that gut microbiome community alterations may be associated with many NCDs, including arthritis, asthma, heart disease, cancers, diabetes and neurological disorders. Although there is a lot of research to be done to explore these associations and how they might be mediated, the observations begin to provide new insight into far-reaching effects of diet-induced alterations in the gut microbiome on NCDs. Thus, microbiota-focused precision nutrition could facilitate the design of personalised diet interventions to affect host metabolism, which potentially could protect against diet-induced obesity, and other clinically relevant aspects of metabolic disorders.

The new understanding of how the gut microbiome transforms dietary ingredients into metabolic products that affect the human host will probably alter definitions of the nutritional value of food (Green *et al*., 2017). If so, this raises new requirements for an evidence-based framework to inform consumer and regulatory decisions and new challenges for harmonising standards across national boundaries in terms of the implications for testing, labelling and advertising. To capitalise on these potential scientific opportunities for healthy diets, there is need for considerable basic and applied research, including: how the microbiome affects biology; the extent to which it is possible to reshape microbiome functions through diet; and the assessment of safety and efficacy of bioactive products from the microbiota that may have implications for the increasing use of functional foods. It is also worth noting that the broad scientific advances in microbiomics is bringing into range new opportunities to influence functions in livestock and marine organisms (Chapter 5) and soil (Chapter 6) as well as human health.

4.7.4 Personalised nutrition

The relationship between food and health is complex and subject to influences by the microbiota, the environment, family and society, and genetics. The advancing study of the role of diets in modifying gene expression and of how genetic makeup influences dietary effects on physiology, metabolism and health offers great potential for better understanding of the relationships between nutrition and health and paves the way for personalised nutrition as an important component of personalised health.

New technologies including genomics, proteomics, metabolomics and integrated systems biology approaches help to characterise phenotypes more precisely. Metabolic phenotyping is central to the emerging model of personalised nutrition. As described by EASAC, it is expected that classifying individuals on the basis of their metabolic phenotype and tailoring dietary advice to different groups of individuals will improve the efficacy of interventions. It is hoped that personalised nutrition, coupled with self-monitoring, delivered through smart technologies, will not only help to educate consumers on nutrition-health linkages but will also provide an incentive to change eating behaviours.

4.8 Nutrition-sensitive systems

As described in the preceding sections, there are many factors to be considered for transforming diets for healthier outcomes. Healthy food environments are those that enable consumers to make nutritious food choices, but they do not guarantee nutritious food choices. As discussed by NASAC, the term 'food environment' refers to the physical, economic, policy and socio-cultural surroundings, opportunities and conditions that influence food choices and nutritional status. In turn, accessibility, affordability and acceptability are influenced by consumer food preferences and knowledge. Making more nutritious food options available to a wide range of consumers may influence public health outcomes—but this requires public and private sector investment in research and innovation to identify those gaps in consumption across the human life cycle that contribute to malnutrition to retain and improve the nutritional value of foods, and to increase the acceptability of healthy foods.

The section on food processing in the preceding chapter introduced some of the commercial opportunities for innovation in food products. EASAC discussed how significant opportunities are emerging from responsible research and innovation, based on collective engagement between business, public sector researchers, policy-makers and the public, to align the innovation process and its outcomes with the values, needs and expectations of society. Innovative foods and diets require technical and social innovations, and regulatory innovation that will enable those technical and social innovations. There are already good examples of innovative partnerships, reviewed by EASAC, but some of the innovation requirements have implications for institutional and political innovation and these implications mandate wider stakeholder engagement (see Chapter 7 for further discussion).

As highlighted by IANAS, health education and information programmes are also essential to promote sound nutrition in public engagement exercises, and the same principles must be applied to improve institutional diets, for example in schools, hospitals, and maternal and child healthcare systems, to influence consumption patterns and health outcomes for future generations.

Media and social media are powerful tools to inform and engage but more research is needed here too in order to design effective interventions. For example, as discussed by NASAC, governments may ban advertising of unhealthy foods on national media in Africa, but it is not known which media have most influence on behaviour, particularly among the millennial population cohorts. For the future, mobilising consumer choice requires a better evidence base and better use of the evidence in education programmes and food labelling information, together with smart systems for monitoring consumption behaviour and nutritional outcomes and for providing an early warning on health outcomes, perhaps particularly the likelihood of NCDs.

5 Agricultural productivity and its transformation amidst uncertainty

'*The constraints holding back the competitiveness of African farmers are increasingly shifting from problems of remoteness to a lack of science-based best practices*'. NASAC

Total factor productivity (TFP) is the measure of the efficiency with which inputs are transformed into outputs and, for agriculture, it is the ratio of outputs as crops and livestock to inputs, which include labour, land, fertiliser and use of machinery. According to the Global Harvest Initiative[23], TFP growth is not accelerating fast enough to achieve sustainable agriculture goals. In particular, the TFP growth rate in lower income countries is insufficient to attain the objective of doubling agricultural productivity for small-scale farmers as outlined in the SDGs. However, it is also important not to concentrate on increasing TFP if that leads to reduction in environmental protection. The total resource productivity (TRP) is a measure developed by the OECD that extends TFP to include environmental resources (goods and services).

As observed previously in our report, taking an integrated food systems approach (demand-side as well as supply-side actions) might not mandate such large increments in agricultural productivity, depending on the region, to satisfy FNS objectives; nonetheless, it is prudent to examine all options for improving productivity. There are many sorts of innovation in agricultural productivity—not just technical but also innovation for the farmer and society. Agricultural extension services need to be better supported and more closely aligned to priorities for introducing innovation across the value chain. Moreover, vocational education and training systems need strengthening to enhance the human resource base of farming and building the capacities of innovation. There is a global opportunity for research to identify best practices that fit well into local circumstances. This could also be a significant investment for increasing the attractiveness of rural opportunities for youth.

As discussed, previous improvements in FNS can be linked to advances in scientific discovery and technology development. More research and innovation (technical, social and business) are needed to meet the demands of producing more food with less resources and at a time of changing environmental conditions. There have been many reviews on the priorities, some discussed by our regional reports, and these will not be repeated at length here. We emphasise the imperative to continue committing to agricultural R&D and it is encouraging to see that investment by middle-income countries is now rising (Pardey *et al*., 2016). There are opportunities for new models for investment. For example, it has been proposed that the lessons learned in the successful application of the Global Fund model for infectious diseases might now be applied to smallholder farming and improving nutrition (Sachs and Schmidt, 2017). Other options for shared research platforms include the proposed Global Crop Improvement Network (Reynolds *et al*., 2017) to leverage global expertise and technologies. Such an initiative, on staple crops, could provide access to well-controlled field laboratories while harmonising research practices, using common standards and sharing data. Moreover, combining cropping systems research with socio-economic analysis would improve understanding and modelling capabilities of crop responsiveness to environmental change, and promote uptake of improved practices. To be successful, a global initiative requires multiple funders and research partners, including CGIAR, national agricultural research systems, academia and the private sector (industry and foundations).

Discoveries, often arising from advances in fundamental science, can lead to significant changes, for example in precision agriculture and in plant and animal breeding. In this chapter, we describe some of these advances, without attempting to be comprehensive, and refer to case studies from the regional reports to illustrate the considerable breadth of the relevant science. In addition to identifying where knowledge gaps can be filled, we reiterate that there are also numerous opportunities to use the evidence that is currently available to inform policy and practice. Academies of science recognise their role and responsibility to lead in doing this. However, some of the issues are controversial and conflicting voices complicate decision-making. A recent case study on the damage to olive trees by the *Xylella* bacterium published by the Lincei Academy (Bassi *et al*., 2017) emphasises the necessity of basing decisions on sound agronomic research rather than on intuition and prejudice.

5.1 Farming structures

Farm size and diversity of agricultural production vary substantially within and between countries and regions. This variability is a key structural determinant of FNS

[23] Global Agricultural Productivity Report 2017: www.globalharvestinitiative.org. The Global Harvest Initiative is supported by private sector food and agriculture companies.

(Herrero *et al*., 2017). For the future, there will be new diversity that will affect how we define what a farm is. For example, various developments in cultivation in indoor farming, in urban (European Parliamentary Research Service, 2017) or other contained settings (e.g. vertical farming)[24] may help to decouple food production from land use. Nonetheless, significant economic and other research is needed before the potential value of new farming developments can be assessed.

For the present, more than 80% of smallholder farms in the world are in Asia and Africa; in the Asian region, 90% of all farms are cultivated by smallholders (Teng *et al*., 2015). There are significant opportunities to use large-scale research networks of smallholder farms to share good practice for agricultural productivity and sustainability (Anon. (2018), discussing a Chinese project for large-scale evidence gathering and implementation).

Global analysis indicates that efforts to retain production diversity as farm sizes increase are essential to maintain diverse nutrients and viable, multifunctional, sustainable landscapes (Herrero *et al*., 2017). As discussed by NASAC, while African agricultural transformation from subsistence-oriented, farm-centred systems is already actively addressing rural poverty, the high number of smallholder farm families in some countries justifies specific focus to increase resilience in the face of the threats posed by climate change (see next section) and other pressures on livelihoods, and to meet the need to transform those livelihoods along sustainable pathways. AASSA also described initiatives aiming to diversify diets and improve nutrition in smallholder farms, for example by focusing on the production of perishable, nutrient-rich foods. As IANAS noted, for many countries in the Americas there is a trade-off between high investment, high efficiency agricultural systems and smallholder farms. This social trade-off is a major public policy issue but it is also important to appreciate that all agricultural systems can benefit from advances in science and technology. Whether small- or large-scale, if agriculture is to be resilient, there is considerable scope to address biotic and abiotic constraints, promote sustainable intensification and integrate technical developments with social sustainability and well-being of the rural population. As emphasised by IANAS, at the country level as well as at the farm level, science, technology and innovation are as essential for productive capacity and competitiveness as to the search for an eco-efficient agriculture. This becomes even more critical for countries that are not self-sufficient in food production.

5.2 The challenge of climate change for agriculture

Broad issues for climate change and food systems were discussed in Chapter 3 and those for diets were discussed in Chapter 4. As the regional reports discuss in detail the various specific impacts of climate change on agriculture and the possibilities for adaptation, further comprehensive review of the literature is not now provided here. However, we list some recent evidence (mostly published since the regional reports were prepared) to illustrate the range of research underway:

- Extreme weather conditions and climate anomalies account for 40% of global wheat production variability (Zampieri *et al*., 2017).
- Increased temperature may accelerate development of resistance to Bt biotechnology-based agriculture pest management (Venugopal and Dively, 2017).
- Projections from analysis of US Department of Agriculture data indicate that climate change could eventually overwhelm all gains in US agricultural productivity since 1981 (Liang *et al*., 2017).
- Various parts of Africa could become unsuitable for some staple crops by 2100 because of temperature rise, in particular legumes, banana and maize (millet, sorghum, cassava, groundnut and yam may be more tolerant to climate change) (Rippke *et al*., 2016).
- Detailed global analysis from the Lancet Countdown initiative (Watts *et al*., 2017) documents effects of climate change on FNS as part of a comprehensive evaluation of impacts on health (see Chapter 4). Among core assessments is the impact of climate change on marine primary productivity.

In addition to the varying effects of climate change on agriculture described above and in the regional reports, recent research discloses a direct negative effect of increasing carbon dioxide (CO_2) concentration on human nutrition. Experimental research shows that CO_2 reduces the level of key nutrients such as protein, zinc and iron, especially in C3 crops (wheat) and legumes (Myers *et al*., 2014). Using the experimental outputs together with information from global databases of bioavailable intakes of nutrients, projections of global risk estimate, for example, that there will be nearly 140 million people at new risk of zinc deficiency, the majority in Africa and Asia (Myers *et al*., 2015). The effects of CO_2 in reducing crop protein content might place an

[24] See, for example, initiatives in Singapore: www.ava.gov.sg.

additional 1–2% of the global population at risk of protein deficiency, also mostly in Asia and Africa (Medek *et al*., 2017). This research in progress, and extension to assessment of impacts of CO_2 on other micronutrients, can guide interventions aiming to reduce key nutrient vulnerability—not just in fortification programmes but also by breeding crop varieties less sensitive to these effects of ambient CO_2.

Taken together, the accumulating evidence mandates coordinated efforts to develop climate-smart agriculture. These efforts need to be comprehensive. CGIAR listed[25] some key innovations for adaptation that included: actions on stress-tolerant crop varieties; agroforestry; aquaculture; improving smallholder dairy; alternative rice systems; solar irrigation; digital agriculture; climate-informed advisory services; weather index-based agricultural insurance; and scaling up of financing for climate change adaptation. Special consideration is needed with regard to women and their access to these inputs, systems and support structures. More often than not, women's access to these strategic resources is constrained. Consideration is also needed for young people to play a significant role in climate-smart agriculture, especially where information and communication technologies can bring new employment opportunities.

Agriculture is itself one of the main sources of GHG emissions and, currently, food systems account for about 30% of emissions (CO_2, methane (CH_4), nitrous oxide (N_2O)) (Carlson *et al*., 2017), about half being derived from agricultural production and half from land conversion. Certain cropping practices contribute disproportionately to particular emissions, for example peatland drainage to CO_2 and rice production to CH_4. Therefore, the issues for agriculture and climate change are not just those for adapting agriculture to climate impacts but also for reducing the contribution of agriculture to GHGs emission and climate change, in pursuit of COP objectives. As discussed by IANAS and EASAC, there is a broad research agenda associated with mitigating the effects of agriculture on GHGs including: attending to soil health; agronomic management practices; land sparing; and promotion of biodiversity. Nonetheless, climate-smart agriculture cannot by itself meet COP emission goals and, as discussed by EASAC, there is also need to reduce waste and to introduce demand-side strategies for influencing those consumer behaviours associated with excessive GHG emissions (see Chapter 4). Further research to evaluate trade-offs between emissions and food security must consider not only food production but also the nutritional value of food (Carlson *et al*., 2017). In addition to climate change impacts, food production and processing have substantial other environmental costs (see also Chapter 6). Recent meta-analysis (Poore and Nemecek, 2018) of the literature on impacts of the different food production systems worldwide is an important contribution to understanding and lessening food's environmental impacts.

5.3 Agricultural productivity and the needs of end users

Although there are many dimensions to improving agricultural productivity, the focus here will be on three particular (albeit broad) themes, drawing on analysis in the regional reports and illustrating the wide range of scientific opportunities continuing to come within range: precision agriculture, breeding technologies and marine/freshwater sources.

5.3.1 Precision agriculture

As observed by AASSA, precision agriculture was born with the introduction of global positioning system (GPS) guidance for tractors in the early 1980s and its worldwide adoption makes this probably the commonest example of precision agriculture today. The introduction and development of precision agriculture is increasingly relevant in improving the cost-effectiveness of agriculture and, by increasing efficiency and reducing chemical inputs, in minimising waste and reducing impacts on the wider environment. The term is now used to cover heterogenous technologies that include autonomous machinery (such as robotics), three-dimensional printing on the farm, use of smart phones, satellite positioning and other sensor systems (see, for example, King, 2017). Developments in image-processing algorithms and artificial intelligence will boost wider use of precision agriculture (Ghaffarzadeh, 2017).

Current and next-generation precision agriculture systems depend on advances in collecting and using data, including real-time data. Open data are becoming increasingly integrated across different scientific activities and from diverse sources (e.g. Earth observation satellites and other remote sensing, social media, crop phenotyping) but, as discussed by EASAC, there are continuing issues with finding and extracting information from heterogeneous data sets. The regional reports all variously describe the increasing value of access to information, data analysis, predictive and early warning systems. The role of information and communication technology (ICT) in aiding the rapid identification of pests and diseases and in mapping their locations and spread is another important tool for

[25] https://ccafs.cgiar.org, in particular Dinesh D *et al*. (editors) (2017) Working Paper on '10 best bet innovations for adaptation in agriculture. A supplement to the UNFCC NAP Technical guidelines'. Research questions associated with developing climate-smart food systems are also discussed in further detail by Whitfield *et al*. (2018).

managing and mitigating risks. Integrating data sets for soil, weather and crop suitability can provide practical information for farmers everywhere and assists in decision-making to minimise weather-related production risks.

For example, NASAC discussed how innovation in mobile phone technologies can spread awareness of new technologies, and practices, can help to overcome trade and market-related information challenges, link farmers to markets and support communication between producers, consumers and researchers. AASSA also described how data and predictive models are increasingly being used to make local decisions about, for example, fertiliser use, pest management, and harvesting—analysis delivered through mobile phones to assist smallholders. ICT innovation can also address wider issues related to the remoteness of communities, through offering banking, credit and other services.

There is a significant agenda for interdisciplinary research among engineers, geographers, biologists and data scientists to develop better integrated sensing and reporting systems, collecting, curating and sharing standardised data (see also Chapter 3) to promote precision agriculture. Capitalising on this research also requires impact analysis to identify and overcome impediments in smallholder and other farm adoption of precision agriculture systems, and the development of new roles for evidence-based extension services. Other issues are addressed in more detail by EASAC. One concern raised is that some technologies in precision agriculture may foster homogeneity. However, if smart farming is really smart, it should have the potential to accommodate heterogeneity. The EASAC report also noted that it is important to introduce precision biology and engineering in other parts of the food system, for example for better recycling, storage, packaging and transport functions, retail environments and their access.

One example, raised by NASAC, AASSA and IANAS, will be mentioned here to illustrate the increasing value of precision agriculture: drip irrigation technology. As reviewed by IANAS, land productivity is increasingly dependent on efficient water use (see also Chapter 6), requiring changes to cropping patterns, innovative irrigation approaches (linking irrigation with soil moisture monitoring and the phase of plant cultivation), and crop improvement strategies, together with novel policies and greater investment in research and capacity development. These requirements are well illustrated in the AASSA case study of drip irrigation technology—discovered and developed locally and now with considerable scope for the region and globally. Because of drip irrigation, crops are now growing in desert and marginal climates that could not otherwise have been feasible, and with significant gains for yield and water conservation. It is noteworthy that this innovation in Asia resulted from private investment in R&D—exemplifying the importance of incentivising and coordinating both public and private sector scientific enterprises. In Africa, experience is also being gained with drip irrigation technology as part of the International Atomic Energy Agency's Technical Cooperation Project. It is also important to appreciate, however, that technical advances cannot happen in isolation from broader development and supporting infrastructure (Garb and Friedlander, 2014).

5.3.2 Plant breeding technologies

There is sometimes a considerable gap between the crop yield in a country and the current highest performance worldwide. For example, as reported by AASSA, the gap in yield between ASEAN countries and the world's highest yield is around 70%, 15%, 65% and 150%, respectively, for rice, sugarcane, cassava and maize (Office of Agricultural Economics of Thailand, 2015) Hybrid rice accounted for only a small proportion of India's rice cultivation – although its use is now gathering momentum – whereas hybrid rice accounts for more than 50% of all rice cultivation in China (Spielman *et al*., 2013; Guohui *et al*., 2014). Rice tolerant to flash floods has now been developed and similar strategies are being applied to develop rice varieties more resilient to various biotic and abiotic stress conditions. There have been significant achievements in yield in Africa but NASAC also attested to the recent declines in cassava, yam and maize in the period since 2008. Evidence indicates that smallholder farmers are largely unable to benefit from current yield gains offered by plant genetic improvement because they farm on depleted soils that are non-responsive to fertiliser application (Vanlauwe *et al* 2015). An integrated land management strategy is needed. Generally, as emphasised by EASAC, it is vital to deploy all available approaches to improving yield, traditional and novel, building on existing achievements for good agronomic practice. The potential costs of not employing a new technology, or being too slow in adoption, must be considered. There is no time to lose in resolving the problems for FNS.

We emphasise the critical importance of taking a comprehensive ecological approach to the challenges for sustainable production, encompassing improved crop varieties, integrated crop protection, soil fertility and water management, with reduction of external inputs. There are major threats to plant health that must be tackled by international cooperation in linking science, economics and policy (Macleod *et al*., 2016). There are also considerable gaps in data assessing plant health and crop losses that need to be filled (Nelson, 2017). Improved breeding programmes are a core part of ensuring sustainable production. Capitalising on scientific advances (using genomic tools) to confer plant resistance to pests is an alternative to the use of pesticides and, together with curation of genetic resources and commitment to the other necessary stages in the plant breeding process, can contribute to sustainable agriculture (Nelson *et al*., 2018).

IANAS described how, although progress is variable, most countries have national breeding programmes to address the challenges of climate and climate change. Furthermore, the conservation of genetic resources *in situ* and *ex situ* is part of most countries' efforts to promote productive capacity. All breeding techniques make use of genetic diversity and change but vary in the precision with which changes can be made. It should be appreciated that, because of the often-long lag times for translating scientific advances into improved crops and livestock, if an appreciable contribution is to be made to attaining SDGs in 2030, then new ideas must be researched and implemented now. Improving plant and animal breeding programmes requires capitalising both on the genetic material collected and conserved in gene banks or other resources, and on the rapidly advancing sciences that cover the spectrum from sequencing to editing genomes and understanding the functional consequences.

Plant biotechnology techniques include tissue culture, marker-assisted selection (the use of genetic markers to promote selection of natural traits in breeding) and the development of diagnostics, all supported by bioinformatics, as well as genetic modification and a newer set of tools collectively referred to as the new plant breeding techniques (NBTs). We do not attempt to be comprehensive here in reviewing biotechnology, and examples of what is possible are discussed in detail in all the regional reports. Nonetheless, we emphasise that there are considerable scientific opportunities for plant breeding to develop new cultivars with higher yield potential, enhanced abiotic and biotic stress tolerance, altered phenological development and improved quality. If organic farming and other specific practices, such as conservation agriculture, are to be made more competitive, then there is also need for more research into these systems with regard to the breeding of appropriate cultivars.

Scientific advances in plant biotechnology are occurring in all regions but the uptake of some of the methodologies for plant breeding and commercialisation has been variable within and between regions. In particular, the acceptance of genetically modified organisms (GMOs) in European and African countries has been mixed, as described by EASAC and NASAC[26]. In the AASSA region, many countries are proceeding with GMO laboratory research but field trials are much less common and genetic modification policies vary widely across the region. In the Americas, the main grain producing and exporting countries (USA, Brazil, Argentina, Canada, Paraguay, Uruguay, Bolivia, Mexico, Colombia and Chile) all use genetically modified crops (mainly soy bean, maize, canola, as well as cotton).

Regulatory delay in approving new crops impacts negatively on food production and incurs high health costs (Wesseler *et al*., 2017). Furthermore, over-regulation in one region may deter innovation in another, as discussed by EASAC with regard to the spillover effects of European policy on Africa. For the current generation of genetically modified crops, it should be noted that there are benefits for farmers' time and effort: research cited by NASAC documents the labour-saving benefits for smallholder farms of herbicide-tolerant maize. Meta-analysis of publications on genetically modified crops cited by AASSA documents the increase in yields as well as reduced pesticide use for genetically modified crops. According to IANAS, among the advantages reported for the use of genetically modified crops are environmental benefits (reduction in use of chemical pesticides, minimal or no tillage to conserve soil, reduction in use of fossil fuels) plus increased productivity per unit land area – with reduced pressure on natural ecosystems – and greater farmer income.

GMOs remain controversial in some regions despite attempts to develop traits of considerable societal value, for example, in Africa, disease-resistant bananas and cassava, nitrogen-efficient rice, insect-tolerant cowpea and drought-tolerant maize. Several countries in the Americas are now developing their own genetically modified crops, for example maize, bean, sugarcane, eucalyptus, potato, papaya, rice and citrus with various improved traits such as virus resistance (bean) and drought resistance (maize).

Building on previous advances in genetic research, NBTs are being revolutionised by genome editing tools, in particular the CRISPR–Cas9 (clustered regularly interspaced short palindromic repeats–CRISPR-associated protein-9 nuclease) system, which allow the alteration of a targeted DNA sequence in a cell, precisely and now relatively easily and cheaply. CRISPR–Cas9 exemplifies a significant advance derived from basic research, the manifold impacts of which would not readily have been predicted. These tools are discussed in detail in the regional reports and in other outputs from the regional academy networks (e.g. the EASAC 2017 report on Genome Editing). In some cases, the NBTs do not result in the presence of foreign DNA in the final crop plant, and in some countries these techniques will face lower regulatory hurdles than have traditional

[26] For the global status of commercialised biotech/genetically modified crops, see ISAAA Brief 2016: https://www.isaaa.org/resources/publications/briefs/52/download/isaaa-brief-52-2016.pdf.

transgenic (GMO) products. However, this status is still debated in some regions and there is lack of consensus on what 'foreign DNA' is. The recent decision by the European Court of Justice to include genome editing within GMO regulations risks inhibiting research and agricultural innovation in the EU. It is important for regulation to be evidence-based, transparent, proportionate and flexible to facilitate future innovation. Innovation is inhibited not just by over-regulation but also by uncertainty in regulation.

This raises a general point emerging from our IAP synthesis work: further international consideration should be accorded to agreeing nomenclature and definitions of terms that currently may be perceived as contentious, subjective or likely to be interpreted differently, for example foreign DNA, GMOs and precision agriculture. Although the issues are sometimes controversial and debate is polarised, there are principles that could be agreed upon: the need for standard definitions; transparency in describing the breeding methodology used; where appropriate, product labelling to enable traceability and consumer choice; and for similar evidence standards and precepts for regulatory frameworks to be adopted by different regions. A case can be made for regulating the trait and/or product rather than the technology used in generating that product.

Genome editing science is proceeding very rapidly. The regional reports provide examples of CRISPR–Cas9-edited commodity crops such as maize, soybeans, canola, rice and wheat to confer, for example, traits of drought and disease resistance and higher yields. Genome editing is also being used to remove food allergens and to increase nutritional content. The potential is high but a fundamental knowledge of the relationship between genotype and phenotype is still essential. Further advances in using genome editing or other biotechnology tools will be facilitated by the ambitions[27] to sequence many more genomes, including the hitherto neglected crops. Global cooperation on the scale needed to do this faces a range of challenges, including funding, agreeing standards to ensure high-quality sequencing and accessing DNA samples from the wild.

As described by all four regional reports, it continues to be important to collect and categorise orphan and other underutilised crops and wild populations of key plant species[28]. Their assessment and use for modern molecular breeding technologies capitalises on the shared resources in gene pools with potential to generate strains with higher nutritional value, increased response to stress and, as part of the diversification of food resources, to mitigate climate impact. One example of the potential to expand use worldwide of a traditional crop is provided by quinoa, exported from Peru and Bolivia and increasingly consumed by middle-class populations elsewhere, for example in Europe, as a healthy food. EASAC described how recent ascertainment of the quinoa genome helps to understand its genetic diversity and provides a basis for breeding quinoa varieties for European domestication, suited to day length and seasonal changes—exemplifying how the interdisciplinary research agenda must consider interconnections between agriculture, nutrition and ecology.

Extensive research is also still needed on the determinants of domestication of indigenous crops and landraces, alongside strengthening of seed quality assurance schemes. For example, AASSA described the use of wild emmer wheat and other wheat relatives in the fight against stem rust. Potential control of the especially virulent form of stem rust, UG99, resides in the introgression of a resistance gene from a wild relative of wheat into the cultivated strain. To capitalise on these natural resources, it is vital to extend efforts to collect, phenotype, genotype, catalogue and preserve the diverse wild relatives and landraces of cultivated crops.

5.3.3 Animal breeding and feed inputs

Advances in animal agriculture have also depended on R&D. Science and technology now have much more to contribute to tackle challenges associated with efficiency of production, animal welfare and antibiotic resistance in farming. Genomics, advances in reproductive biology and stem cell research all have much to offer. At the same time, as noted by NASAC, some indigenous African livestock and fish (and plants), although resilient to many risks and adverse conditions, are viewed as famine foods, only to be utilised in adversity. This behaviour emphasises the relevance of social sciences research, to understand dietary habits and how to inform consumption patterns so as to optimise uptake of indigenous foods.

---

[27] For example, the Earth BioGenome Project that aims to include every major clade of plants, thereby covering orphan crops and high-nutrient plants. Combining these efforts together with an initiative to create an open library of biological data (Bank of Codes) would facilitate tracking of data and could be employed automatically to distribute part of the resultant commercial value back to the country of origin of the DNA sample. The World Economic Forum's Fourth Industrial Revolution of the Earth initiative aims to make data from biological assets available to innovators around the world while ensuring equitable sharing of benefits (https://www.weforum.org, 23 January 2018).

[28] Recent information emphasises the recommendations from the regional reports: the IUCN Red list of threatened species (www.iucnredlist.org, December 2017) describes how species of wild rice, wheat and yam are threatened by extinction. These wild species are important for adding necessary genetic diversity in cross-breeding and as conservation *in situ* becomes more challenging there is increasing need for preservation of resources in gene banks.

As discussed in the regional reports, key livestock research targets include increasing the welfare, productivity and efficiency of animal feed systems and reducing the environmental footprint of livestock production. AASSA reviewed the research requirements associated with developing new feedstuffs (lower down the food value chain) for simple-stomached animals such as pigs and poultry and for exploring the underlying mechanisms for feed conversion efficiency. AASSA also described the potential of combinatorial approaches to meeting human nutritional requirements, for example a meat–mushroom amalgam which extends the use of beef protein, and of alternative food sources, for example algal species (also noted by EASAC) and insects. In this context, AASSA recommended more research and food technology innovation to generate appealing insect-based food products for consumption, together with analysis of trade-offs required. For example, producing housefly larvae meal may decrease land use but increase energy use.

EASAC described recent advances in sequencing and editing genomes that are expected to revolutionise the breeding of farm animals: to enhance livestock health and welfare as well as to confer productivity traits. For example, genome editing in pigs is currently being used to introduce disease resistance (particularly, protection from African swine fever and the porcine reproductive and respiratory syndrome virus) and to increase muscle mass by modification of the myostatin gene. NASAC described a genetic research case study on African trypanosomiasis that offers potential value compared with previous methods of prevention by conventional breeding programmes or vaccines, or control by trypanocidal drugs.

One critical part of establishing productive mixed farming systems – and stable protein sources – is to ensure availability throughout the year of high-quality feed for livestock, emphasised in the NASAC and AASSA reports. NASAC reviewed recent research on the production and use of high-quality forage grasses and legumes, with potential benefits for restoration of degraded land as well as increased livestock productivity. However, grass breeding programmes are still limited because of lack of funds to characterise and utilise the gene banks of forage species, such that genetic variability is still largely untapped. This remains a considerable scientific opportunity: NASAC described in detail a case study on *Brachiara* grasses and discussed the value of a wide variety of alternative local feeds for livestock.

NASAC and AASSA indicated that there is also a significant research agenda associated with the following:

(i) Assessment of appropriate combinations of forage species to sustain nutritionally stable swards throughout the year under different agro-ecological and management systems, taking into account the changing climate.

(ii) Understanding how feed can boost animal productivity in terms of the influence of poorly digestible components or particular nutrients. Research is cited on cowpea varieties in Nigeria, assessing food and fodder characteristics including nitrogen, fibre, energy content and digestibility. There are also implications for further understanding of the gut microbiome and for using forage traits in crop breeding targets.

5.3.4 Marine and freshwater sources of food

Fish and other aquatic sources comprise about one-third of animal protein intake worldwide. However, as noted by EASAC, current fish capture from the wild seems to have reached an upper limit and the exploitation is unsustainable. Because of declining marine fish populations, it has been estimated (Golden *et al*., 2016) that an additional 10% of the global population could now face micronutrient and fatty acid deficiencies, especially in developing nations at the equator.

Yet compared with land, the marine environment seems underutilised as a food provider for human populations. As reported by EASAC, the ecological efficiency of fish capture from the wild is at least an order of magnitude lower than for human food produced on land: exploited fish stocks represent only a minor fraction of the total marine biomass. Current fishery practice is based on a long tradition of hunting predators high up in the food chain. EASAC recommended directing capture fisheries towards lower trophic levels in the marine food chain—it is recognised that this redirection presents technological and management challenges. There is further scope for transferring water-intensive components of the human diet (e.g. animal protein) from land to the ocean and there is urgent need to explore the knowledge base for sustainable harvesting and culturing in marine and freshwater.

What about fish farming? According to AASSA, aquaculture is regarded as one of the fastest growing food sectors worldwide. IANAS discussed how aquaculture has emerged as a major new industry in a wide range of countries (in Canada, Chile, Mexico, Peru, Argentina and Ecuador). However, on the basis of present production and distribution patterns, there is doubt that the global increase in fish farming could meet the projected nutritional shortfall (Golden *et al*., 2016). Moreover, there is evidence that fish from aquaculture are poorer in micronutrients compared with captured fish (Thilsted *et al*., 2016) so efforts may be needed to increase micronutrient density in farmed fish. According to these assessments, new models that integrate data on human health and

Box 4 Aquatic case studies from the regional reports

NASAC. Octopus seasonal fishing in Rodrigues (an island off the coast of Mauritius). Previous over-exploitation of this resource was addressed by multiple actions including an education campaign for fishermen (to cease fishing during the breeding season), restoration of mangrove plantations, control of invasive plant species, and enforcement against poaching and illegal trade, with the net result of considerable improvement in catches. This programme has now been extended to other African countries and demonstrates the importance of eco-agricultural research informing policy and practice. IANAS referred to other environmental regulation and conservation of biodiversity actions in the Americas that have also acted to favour species protection and to some extent moderated over-exploitation.

AASSA. Asian shrimp production. Because males are much larger than females, the prawn industry would benefit from a breeding technology yielding only males. RNA interference has been used to silence a gene encoding insulin-like androgenic peptides and the resulting feminised males produce only male offspring. In regional cooperation, the juvenile feminised prawns are now distributed throughout Asia for commercial production and, additionally, they might be usable as sustainable biocontrol agents against freshwater snails that carry disease (including schistosomiasis) or damage rice paddy fields. As these prawns cannot form reproductive populations, there would be no risk of them becoming invasive species.

AASSA. Tilapia lake virus. Tilapia are farmed globally as an important source of protein but Tilapia lake virus, identified in 2014, poses a great threat. Despite its very recent discovery, the virus has already been sequenced, an important step in producing a diagnostic kit and the first step in developing a vaccine.

IANAS. Fish farming in South America. Chile is now the second largest producer of salmon worldwide. Rainbow trout is also found as a naturalised population in about half of the countries of South America, from the Venezuelan Andes to the southern areas of Argentina and Chile.

fisheries must be developed to design nutrition-sensitive policies for fish production; reform aquaculture to improve access by marginalised populations; and build new interdisciplinary partnerships among scientists, aquaculture technologists, nutrition and public health specialists, economists, funders and policy-makers. Furthermore, it is deemed essential for fisheries policy to support socially responsible as well as environmentally sustainable actions: to address the labour rights abuses in the sector and be responsive to all stakeholders (Kittinger *et al*., 2017). In addition, it is also increasingly important to address the environmental implications of mariculture, for example in ocean cultivation systems.

The regional reports describe a range of case studies and scientific opportunities that illustrate the further potential of the oceans and aquaculture. Such case studies (for example those in Box 4) need to be carefully monitored to share lessons of success within and between regions.

Globally, the aquaculture sector is significantly behind plant and livestock production in applying selective breeding, but there is potential to increase yield to augment the other strategic actions reviewed by Golden and co-workers (2016). Genetic improvement could also reduce the environmental impact of aquaculture. For example, research cited by NASAC on the African catfish established that increase in feed conversion efficiency consistently reduces the environmental footprint—although research is still also required on the best management practices to maximise productivity sustainably. Broadly, there is much more to be done to evaluate the complex interplay between fisheries, aquaculture, agriculture and the environment in addressing trade-offs to meet the SDGs (Blanchard *et al*., 2017).

6 Competition for natural resources: sustainable development and the wider ecosystem

'*If the principles of natural resource economics were applied to agriculture, whereby all externalities were fully costed and the costs internalised into the costs of production, there would undoubtedly be significant shifts in the type of food production*'. AASSA

Forty per cent of the Earth's land surface is accounted for by agriculture, either growing crops or raising livestock. Water, energy and soil are essential for food production and their availability is also directly related to current and future FNS. Consumption of the Earth's natural resources has doubled in the past 30 years, with a third of the planet's land now severely degraded[29]. Reversing trends in the condition of land and other natural resources could accelerate efforts to achieve many of the SDGs. However, there is still escalating competition between the demand for land functions that provide food, water and energy and other ecosystem services: delivering a more secure future requires better management of trade-offs at a landscape scale. It may be that optimised land use futures will deliver fewer services than are currently demanded. The modelling of alternative futures for delivery of services must cover multiple intersections, including health–nutrition–economy–climate–ecosystem services.

As mentioned previously, competition for the limited land for agriculture comes from urbanisation, industrialisation and conservation. The proportion of the population worldwide living in urban areas rose from 33% in 1960 to 54% in 2014, with particular growth in Asia and Africa, although rural decline is a global issue (Liu and Li, 2017). NASAC also highlighted the impact of foreign investment in land. Africa is the continent most targeted for large-scale land transfers to foreign owners, mainly readily accessible, fertile land. A large proportion of land acquired by foreign investors is often not used immediately and the rate of abandoned projects is high. Land acquisition and change in usage needs to be closely monitored and the impacts determined on food security at different levels—national, community and household and among different groups such as women and marginalised communities.

In all regions, large changes in land use have occurred in recent decades to enable the expansion of agriculture. Agriculture competes with other ecosystem services for land use and, in addition, agriculture may have direct impact on other ecosystem services. For example, many current agricultural practices negatively affect communities of pollinator species, as well as parasitoids that provide natural control of pest species. The conversion of natural ecosystems to farmland directly reduces the availability of essential resources for many beneficial species. Furthermore, adoption of large-scale agriculture creates more simple landscapes, which are more uniform, reducing the biodiversity and the services they provide. In addition, the frequent application of insecticides, herbicides and fungicides in agroecosystems have both direct (toxicity) and indirect (resource availability) negative effects on beneficial species, leading to a reduction in important ecosystem services.

As observed by IANAS, agricultural expansion now threatens ecological equilibria and biodiversity and is intensifying regional and global climate change. AASSA also provided a comprehensive assessment of resource competition on the basis of social, economic and environmental issues for land and water competition. For example, in China, as elsewhere in Asia, the rapid movement of rural dwellers to urban areas has implications for dietary changes (Chapter 4) but urban development has many additional implications for using and polluting land and water resources. Most studies on how urbanisation affects food systems have focused on the impacts of physical expansion of cities on land use for agriculture (supply-side issues) and changes in diet (demand-side issues) and, of course, these are highly important dimensions. However, research is also needed on the multiple, less-studied aspects of urbanisation and food systems (Seto and Ramankutty, 2016), for example linkages with food waste, urban retail systems, urban areas as hubs of innovation and the impacts on smallholder farmers who are displaced by urban expansion. Further discussion of the multiple effects of urbanisation on food systems, in particular on diet quality, health, food access and food choices, is provided in IFPRI (2017b). Bloem and de Pee (2017) examine the effects of variation in urban size, dynamics and infrastructure in determining access to nutritious foods.

At the same time as demand for land for agriculture increases, there are additional demands for land for carbon capture and storage (e.g. by reforestation) and for other purposes, in particular the bioeconomy. As discussed by EASAC, the research challenges associated with multifunctional land use planning

[29] 'UN Global land outlook. Better land use critical for 2030 agenda', September 2017. On www.global-land-outlook.squarespace.com/the-outlook/#the-book.

include developing scenarios for balancing food, energy, water and environmental objectives; assessing the validity and usability of different approaches to valuing ecosystem services; and improving the ability to analyse risk and opportunity in decisions about trade-offs between different ecosystem services. There is need to develop a better evidence base to underpin land, water and other resource use in providing the range of private and public goods required, in a sustainable way appropriate to place. Because there are very few spontaneously occurring markets for environmental services, their under-provision is an example of market failure such that attention has to be given to the appropriate conditions and incentives to provide public environmental services.

A paper on behalf of the G20 (von Braun *et al.*, 2017) calls for land, water and energy to be considered jointly in policies as part of the re-design of global governance of agriculture and food. In the following sections, we focus on issues raised by the regional reports. However, there are also relevant issues for other resources, such as micronutrients. For example, phosphorus status is of great significance in global food security: to meet projected demands for milk and meat, it has been estimated that phosphorus inputs (mineral and organic) in global grasslands would have to increase more than fourfold by 2050 (Sattari *et al.*, 2016).

6.1 Water

IANAS observed that between 1900 and 2000 the global population increased fourfold but freshwater extraction grew ninefold. If this trend increases, the global rate of water extraction would increase beyond sustainable levels; it has already done so in some areas (e.g. in parts of Asia (Teng *et al.*, 2015)). In all regions, agricultural production is also associated with environmental costs to water, for example as nutrient run-off and eutrophication of water. Globally today, agriculture accounts for approximately 70% of water withdrawals and the UN predicts that irrigation demands will increase by up to 100% by 2025. Recent hydrological modelling and Earth observations have quantified high rates of groundwater depletion worldwide, primarily because of the water withdrawals for irrigation. It was estimated that approximately 11% of non-renewable groundwater use for irrigation is embedded in international food trade (Dalin *et al.*, 2017), highlighting risks for both food and water security globally.

As discussed in detail by IANAS, the efficient use of water resources is essential for future growth in food production, public health and quality of life. In the Americas, poor water quality and inefficient water management are among the greatest environmental challenges. The Americas are rich in water resources but science- and technology-based improvements, especially to optimise irrigation efficiency, are essential to meeting the food producing potential of the region. Water quality is increasingly degraded by contaminants including pathogens, fertilisers, pesticides and others, such as fuels and solvents. IANAS emphasised the importance of better groundwater management in buffering against drought and in supplementing surface supplies. One of the most important strategies employed in more rational water management is the reuse of wastewater in agriculture, although this reuse requires close monitoring, according to the crop under irrigation, because of higher salinity and other possible contaminants.

NASAC reviewed the many challenges relating to water in Africa: for example, arid and semi-arid areas use almost all of their available water resources through irrigation with non-groundwater and many of these countries have to import water to meet their needs. In agreement with the point made by IANAS, NASAC emphasised the importance of recycling wastewater and described advances in hydroponic production with recirculation of water and nutrients in a closed system. Closed irrigation systems consume perhaps half the water of conventional processes; they also extend the growing period into year-round production and protect against plant diseases. Significant investment in science, technologies and skills is necessary in all areas of water harvesting, storage and use (see also Chapter 5 for a discussion of drip irrigation innovation). Many of these innovations have positive implications for women in reducing the burden traditionally borne by them in fetching water for household and agricultural purposes. Access to clean water has benefits for safer food preparation, health and sanitation.

In reiterating many of these points, AASSA additionally described how excessive use of water to grow cotton in Asian/Australasian countries is putting a strain on water resources in general and the food producers specifically. EASAC also focused on the issues for agriculture and water pollution, water availability and water use in the supply chain, including the consequences of water use embedded in European food imports on the rest of the world. The issues for the nexus food–water–other ecosystem services are inherently trans-disciplinary and require collaboration between multiple areas of expertise.

Many of the challenges are similar between the regions, and a report from the CFS HLPE[30] covers the multiple linkages between water and food security, the need to manage water scarcities in agriculture and food systems,

[30] 'Water for food security and nutrition': www.fao.org/cfs/cfs-hlpe.

and the challenges for inclusive water governance, including social and human rights issues. However, there has been less focus on water and nutrition: there are continuing scientific opportunities to facilitate knowledge exchange and co-design research across disciplines at the food–nutrition–water–environment interfaces.

6.2 Soil

Agricultural yields are limited by soil conditions, and global food security is jeopardised by increasing land degradation. A recent FAO report[31] documents soil resources worldwide, the drivers of change, likely impacts and proposed responses.

IANAS described how soil degradation is an important problem in the Americas, requiring research and innovation to find solutions. The use of chemical fertilisers and pesticides is negatively affecting soil microbiota as well as contaminating surface and groundwater resources (see previous section). Excessive mechanisation and compaction of soils are causing an increase in erosion and loss of fertility. The imperative for change in soil management in agriculture has led to direct planting initiatives with significant progressive effects, for example in Brazil on soil protection, conservation and the improvement of soil physical, chemical and biological properties.

NASAC reviewed how declining soil fertility is a major constraint to agricultural transformation in Africa. Integrated land management must focus on raising organic matter content, moisture retention and other forms of soil rehabilitation. Furthermore, comprehensive soil mapping is necessary to identify deficiencies and to underpin soil improvement practices. Combining soil mapping with weather monitoring and crop suitability mapping will help to deliver precision agriculture (see Chapter 5). AASSA described how soils have been contaminated with heavy metals, with the problem extending through South and South-East Asia. Similarly, EASAC discussed soil nutrient losses and soil contamination and the linkages of soil health problems with food safety and food quality. However, because Europe can import from elsewhere, net food availability is not currently much affected by local soil conditions (although traditional local food producing activities can be endangered). This again illustrates the general point that some regions continue with unsustainable use of resources, including land and water, by exporting the negative impacts to other regions.

As described by EASAC (and illustrated in the other regional reports), among the scientific opportunities in supporting resilient and sustainable soil management are the following:

- Development and introduction of practices and technologies for cost-effective soil management, including conservation agriculture, and reduced use of nitrogen and phosphorus fertilisers. Studies show that organic agriculture has positive effects on soil health but, to reiterate, there is need for research to reduce the yield gap to benefit from the positive effects of this farming practice.
- Improved observation systems for monitoring of soil chemical and biological contaminants.
- Development and introduction of techniques for soil re-carbonisation, restoration and remediation.

Substantial amounts of nitrogen are lost from soil into the air through the process of denitrification, which includes production of the major GHG N_2O. Among innovative soil management practices that need to be developed are those to enhance nutrient use efficiency by crops. AASSA described how synthetic biology advances are leading to developments which can improve soil health. For example, engineered bacteria can be added to soil to drive the fixation of nitrogen in air to ammonia, to fertilise plants.

There is a promising research agenda associated with establishing the functions of the soil microbiome – the microbial communities living in close association with plant roots – on soil and plant health[32]. For example, NASAC described the involvement of the soil microbiome in the reaction of plants to environmental stresses such as high salinity and low water availability, and to diseases. A mixture of traditional research methods, the laboratory isolation of microbial strains, together with modern high-throughput sequencing is helping to catalogue microbial species associated with plants in different soils in sub-Saharan Africa (and in other regions). Recognition of the effects of the soil microbiome on plant productivity must now also be considered in focusing on desired traits in crop improvement programmes: jointly selecting beneficial characteristics in the plant and microbiome. As discussed by EASAC, there is also continuing research required to clarify plant root-soil microbiome interactions in augmentation of carbon sequestration in soils. Understanding the scope and efficiency of

[31] Intergovernmental Technical Panel on Soils, 2015.
[32] One recent publication (Li *et al*., 2018) describes opportunities for new diagnostics for plant health and precision agriculture. Acid rain can damage rice but current methods of monitoring are slow (by the time damage is observed it is irreversible). A new sensing approach measures the impact of acid rain in terms of the root secretion of organic molecules that are food for microbes that then generate a weak electric current. Bioelectrochemical monitoring offers the prospect to measure and transmit this indicator of plant stress within minutes, facilitating remedial action (application of clean water).

this potential re-carbonisation will help to quantify its relative contribution as a negative emissions technology in climate change mitigation. While the gain in soil quality from promoting this interaction could be at least as significant as the effect on GHG levels, the evidence base needs to be strengthened to determine whether the approach could be deployed at sufficient scale and would be economically viable compared with alternative actions (including use of other negative emissions technologies) on climate change.

There are other significant opportunities for research on the soil microbiome in pursuit of the bioeconomy, as outlined by EASAC. In particular, there will be new microbial sources of chemical leads to novel pharmaceutical agents (see, for example, Maffioli *et al*., 2017). Such efforts, in pursuit of novel pharmaceuticals and other high-value chemicals should be extended worldwide in pursuit of the global bioeconomy.

6.3 Energy use and generation

As discussed previously, food, water and energy are interdependent resources that merit integrated management. Agriculture and the food system currently account for about 30% of the global energy consumption (reviewed in further detail by EASAC) and the implications of this consumption, together with the effects of agricultural practices on GHG emission, were described previously. However, there are also constraints on farming from lack of energy availability.

In various regions (particularly parts of Africa, Asia and the Americas), off-grid villages may lack food security because of the reduced capacity to run equipment needed for cultivation and irrigation and an inability to develop local small-scale food processing and prevent post-harvest losses. The implications of constraints on energy use and the possibilities for smart energy provision in achieving food security in off-grid villages are discussed in further detail by Swaminathan and Kesavan (2015), as part of the global Smart Villages project[33]. Efficient energy provision has significant benefits for reducing arduous household labour, and in the preparation and storage of food to improve nutrition. Access to energy can liberate women's time and facilitate employment.

There are also complex issues associated with land use and the competition between food and bioenergy production in agriculture. Bioenergy production may compete with the food sector, either directly, if food commodities are used as the energy source or indirectly, if bioenergy crops are cultivated on soil that would otherwise be used for food production. Countries are shifting to biofuels to meet their increasing energy needs. For example, as described by AASSA, China has implemented incentive programmes to increase biofuel production and currently is the world's fourth largest producer. There are concerns, however, that production of biofuels in China (and elsewhere) is reducing water quality levels and draining water reserves. IANAS indicated that the water requirements used to irrigate crops grown for biofuels can be much larger than for the extraction of fossil fuels. Therefore, biofuel-based subsidies and practices that incentivise farmers to pump aquifers at unsustainable rates, leading to depletion of groundwater resources, must be discouraged. However, water use depends on the crop: for example, grain and oil seed crops are much more water intensive than sugar cane, depending on the specific climate conditions and whether irrigated or not.

As discussed by EASAC, growth in biofuel production is accompanied by increased output of high-protein animal feed co-products from the biofuel processing, but these co-products are often ignored in models of the economic and environmental impacts of biofuel production. In addition to making better use of the evidence base already available for deciding on options about biofuels, EASAC concluded that there are still numerous bioenergy research issues to clarify and resolve. These issues include evaluating the impact on land use; impact on producer price-setting and the likely implications of the market introduction of advanced technologies for biofuel production; and exploring further the complex relationship between bioenergy expansion and agricultural commodity price increases. International disputes are more likely if there is lack of agreement on what constitutes sustainable biomass for bioenergy generation (and for other applications of the bioeconomy): standardisation of biomass sustainability criteria (Bosch *et al*., 2015) must incorporate social as well as environmental and economic factors. There is also substantial research still to be done to elucidate the value of second-generation biofuels (including inedible parts of plants) and third-generation biofuels (including from algae) as well as the longer-term potential for engineering improved photosynthesis.

6.4 Biodiversity

Land use changes and related pressures have already reduced local biodiversity interactions beyond its recently proposed planetary boundary in about two-thirds of the world (Newbold *et al*., 2016). For example, as reviewed by IANAS, conversion of land for agriculture is estimated to account for 80% of deforestation worldwide, leading to other environmental degradation. Throughout the Americas, the conversion of forests to

[33] www.e4sv.org.

farmland increases erosive processes and destabilises hydrological systems, with high negative impacts on quality of life, especially for poor and rural populations.

Widespread transgression of safe limits suggests that biodiversity loss, if unchecked, will undermine efforts towards achieving the SDGs (Newbold *et al*., 2016). The reduction of insect and bird populations reported from many world regions needs coordinated monitoring and more consideration in landscape systems in the future (Foottit and Adler, 2009). Agrobiodiversity is also particularly important in increasing the resilience, sustainability and nutrition security of food systems[34]. Enhancing this use of biological diversity in sustainable agriculture and food systems requires integrating research streams on food, nutrition, health and disease, with research on genetic resources, governance and institutions and social–ecological interactions (Zimmerer and Haan, 2017). EASAC discussed how different parts of the world are aiming to reconcile the conflict between agriculture and wild nature in varying ways; recently with particular regard to objectives within the SDGs, as reviewed, for example, in the work of the International Institute for Applied Systems Analysis[35]. Ecosystem services – including food provision – make important contributions to multiple SDG targets (Wood *et al*., 2018b), highlighting the importance of integrating environmental science into understanding interactions between different SDGs.

In summary, environmental degradation is a major problem that threatens future growth in food production. Integrated landscape management to deliver ecosystem services is a priority research area that needs to be well linked to the other priority research areas covered in this chapter: understanding the drivers and implications of land use change; improving water management and water use efficiency at multiple scales; and improving soil health, nutrient management and nutrient use efficiency.

Many of the issues discussed in this chapter are also particularly relevant to considerations of rural development. There are significant opportunities to use big data sets to monitor the status of rural communities and their environments, to understand rural responses to globalisation and climate change, and to evaluate the effectiveness of different forms of land consolidation. Multi-disciplinary research is again essential, to test policies and technologies proposed to improve agricultural production and rural livelihoods, informing global rural planning and promoting cross-national collaboration (Liu and Li, 2017).

[34] BioVersity International, 'Mainstream agrobiodiversity in sustainable food systems': www.bioversityinternational.org/mainstreaming-agrobiodiversity; and see previous discussion on importance of preserving wild species of crops.
[35] www.iiasa.ac.at/web/home/about/news/150312-World-in-2050.html.

7 Enhancing R&D and science advice

'*The long period of low incentives for agricultural development seems to be coming to an end and there are signs of a repositioning of the role of agriculture in development strategies. Agriculture is increasingly seen as a dynamic sector and an agent for the transformation for national economies. There is frequent mention of a new bioeconomy, where, in addition to the traditional functions of producing food and fiber, agriculture is also seen as playing a strategic role in building a society less dependent on fossil fuel resources, through the production of energy and industrial raw materials that are more environmentally friendly. This epochal change further anticipates a reinvigorated period of innovation and a range of new agricultural research opportunities.*'
IANAS

Our report started from a perspective on international public goods for planetary and human health, aligned with the broad framework represented by the SDGs. The preceding chapters have discussed diverse opportunities and risks. The present chapter further considers how science can be supported and mobilised to address the issues for FNSA. This requires building better connection for science with the policy processes. Improving connectivity at the science–policy interface can build on the lessons learned from what has already worked well in this regard[36]. What are the entry points for the scientist in providing evidence? How can younger scientists be involved? How should the use of science to inform policy be monitored to continue creating a culture of engagement? This chapter summarises what needs to be done both to build scientific capabilities and to connect science with policy.

7.1 Issues for building research infrastructure, collaboration and effective translation

Our report has focused on scientific opportunities for FNSA. To capitalise on these opportunities requires improving research infrastructure, prioritisation and coordination. Reasons for doing this were introduced in Chapter 2 and discussed in the subsequent chapters. In many countries, IAP member academies already have a role and responsibility in helping to build research critical mass and, by sharing their knowledge and expertise, they can also help to promote capacity in newer, smaller academies.

To summarise, among the necessary factors for enhanced research design, translation and impact are the following requirements:

- Engagement of the scientific community worldwide with users of research (including extension services) and the public-at-large.
- Involvement of stakeholders throughout the research process, including design.
- Ensuring effective collective action: improving coordination between different research funders in addressing priorities and supporting initiatives for regional funding.
- Building research capabilities with clear, long-term commitment to human resources, infrastructure and funding.
- Recognising that current academic research, teaching and career structures tend to be organised on a disciplinary basis. There is need to find inter- and trans-disciplinary solutions for FNS. The trends discussed in previous chapters, for example bringing together efforts from different disciplines from hitherto separate themes such as sustainability, health and agriculture, have significant implications for the organisation of the science community. Issues for education need to be considered at multiple levels (Box 5).
- Building partnerships between the public, private and non-governmental organisation sectors[37]. The low research participation by the private sector in many countries is deemed a deficit. Again, there are challenges for the science community in addressing tensions associated with collaborations between different sectors.
- Promoting science and technology cooperation between regions.
- Building leadership capabilities in science, technology and innovation in countries, to manage the dynamics of change around competing priorities and demands.
- Aligning research priorities with development priorities. Capitalising on existing government programmes and policies and with development agency objectives.
- Addressing constraints in the uptake of research outputs and adoption of technology. Better communication of science and innovation advances

[36] For example, the introduction of a sugar tax in many countries is one example of policy-makers taking heed of scientific advice (Briggs, 2016).
[37] For example, the pioneering joint initiative by the EU and the Bill and Melinda Gates Foundation to invest more than €500 million in agriculture particularly to address pressing challenges posed by climate change: https://www.euractiv.com/section/development-policy/news/eu-and-gates-foundation-pledge-e500-million-for-innovations-in-agriculture/, 13 December 2017.

Box 5 Education and training for FNS

A wide range of opportunities and needs in education and training are described in the regional reports. We do not attempt a comprehensive review here; rather, we identify several issues to illustrate the importance of considering requirements at multiple levels:

- In higher education, NASAC observed how there is no traditional field of study for food security. Few international programmes train nutritionists in food security issues and nutrition is rarely integrated into training on agricultural production. NASAC described other major deficiencies in nutrition training in many African countries and drew attention to the steps for curriculum development, and for obtaining experience in practical settings, that need to be taken to fill human capacity gaps.
- AASSA discussed education requirements for health professionals and the necessary trans-disciplinary basis for training in agriculture, nutrition and food, for scientists and technologists. EASAC highlighted the need for better nutrition teaching in medical schools. IANAS emphasised issues for strengthening education and training in food systems and in agro-food research and education together with reviving schemes for international exchange in graduate education for agriculture and related subjects.
- All regional reports discussed how it is not just a matter for higher education. Linkages between nutrition, lifestyle and health must be emphasised throughout education systems and in national public health campaigns.

(and investment opportunities) to policy-makers and the public.

Many of these research infrastructure points have been discussed in detail in the preceding chapters and in the four regional reports. Two particular priorities are highlighted in the section below.

7.1.1 The added value of trans-regional research

All of the regional reports emphasise opportunities for trans-regional research (see also Chapter 2) but the case is perhaps described most persuasively by EASAC, in describing present EU structures and objectives, and by AASSA in terms of its scenario for the Asia region. AASSA recommended leveraging current national strengths in constituting well-resourced regional centres of research excellence (and training), focusing on key opportunities for diversity in FNS and on the territories and population groups at most risk. On the basis of systems analysis and emerging platform technologies, AASSA identified a set of trans-regional research priorities that spanned the following areas:

- Genome-based approaches to plant and animal breeding.
- Big data capture and analysis, and precision agriculture.
- Food technology innovations in harvesting, processing and storage to reduce food wastage.
- Sustainable farming practices for land and water use that also address wider issues for biodiversity and for climate.
- Aquaculture production and integrated farm production systems.

These choices resonate with some of the priorities discussed in the other regions (and in previous chapters) and, although a comprehensive list would include various other priorities, for example for food systems, nutrition and health, AASSA's list illustrates what might be achievable in initial trans-regional commitments focusing on agriculture. Introducing regional initiatives where they do not currently exist to an appreciable degree could also help to complement the established international research organisations such as CGIAR (Chapter 2) or new global initiatives (Chapter 5).
In some cases, virtual cooperative centres could be organised providing that plans with sufficiently specific objectives are clearly conceived. In all cases, there would be significant emphasis on basic science. As noted by AASSA, researchers can and do develop their own international science collaborations but there is a major role for public policy to promote targeted collaborations, and regional and national strategies should allow for, and incentivise, this.

As well as trans-regional cooperation frameworks, IANAS and the other reports highlighted the importance of cooperation between regions, to help identify and correct current weaknesses in pursuit of FNS. In Chapter 2, the initiative of the EU-Africa High Level Policy Dialogue on Science, Technology and Innovation (2016) was commended as a model that may be of more general relevance for building research and innovation coordination between regions, to reduce fragmentation and inefficiency in the cooperation landscape.

7.1.2 Tackling lag times in research translation

AASSA described several examples of the rate of adoption of new technologies in agriculture, where impact is realised only several decades after initial research investment. Because of this extended lag time, it is imperative that funders commit further support to basic research relevant to FNS as a matter of urgency. In addition, all approaches to reducing the lag time should be considered. IANAS observed that implementation of innovation may be limited by availability of capital, scientific capacity and physical infrastructure but also by negative attitudes associated with perceived risks, by excessive regulatory requirements in some countries or by absence of regulation in others. There are critical questions to answer. For example, how to encourage academia and smaller companies to contribute to innovation if a high cost barrier is imposed by inflexible regulation? How to encourage smallholder farmers to take up innovation as part of agricultural transformation?

7.2 Policy issue integration and reform

Previous chapters have discussed many of the opportunities and challenges for using the science evidence base to inform development of policy options. While much of our focus in this report has been on (i) ensuring that this evidence base is robust, relevant and timely, on the basis of verifiable research generated by independent sources, and (ii) that new research effort should be prioritised to fill current knowledge gaps, all of the regional reports also recommend ways to do better in connecting the scientific and policy communities. The policy issues are necessarily complex and inter-connected (see Chapter 2) and, as discussed by NASAC, there are multiple problems currently in devising evidence-based policy. In particular, policy-making and policy advisory activities are both fragmented; there is inadequate monitoring of policy and programme implementation and impact; there is insufficient regional coordination in advising and shaping policy; and sectoral plans may be poorly aligned with development agendas.

As noted previously (Chapter 5 and section 7.1.2 above), research and innovation and their uptake at scale can be constrained both by over-regulation and by lack of regulation, particularly in those areas where technology moves faster than the ability to regulate it flexibly and proportionately. Regulatory hurdles can become a non-tariff barrier to trade. We do not call for global monolithic regulation of technology but rather for agreement to clarify contentious issues, use of consistent terminology and a robust evidence base, and commitment to share good practice in the management of research and innovation[38]. Issues for appropriate regulation are common to many emerging technologies but attention has often focused on the biosciences and on GMOs, in particular. In describing their work to advise the FAO in drawing up guidelines to promote constructive debate, Adenle and co-workers (2018) observed: '*At the heart of the problem is a lack of agreement as to whether and how scientific and non-scientific evidence can and should be integrated into regulatory decision making…*' As described by them, risk analysis frameworks differ: for example, the International Plant Protection Convention, Codex Alimentarius and WTO rules are considered to be based robustly on science whereas the precautionary principle embedded in the UN Cartagena Protocol on Biosafety balances scientific evidence with economic, social and environmental norms. There is need for many countries to develop better capacity to identify and assess relevant socio-economic issues, alongside building regulatory and scientific capacity. In this context, Adenle *et al*. (2018) call for new thinking about how to support training and capacity development to capitalise on existing skills often already to be found in environmental management agencies, food safety agencies and agricultural organisations, together with encouraging the regional harmonisation of risk assessment.

It is not the purpose of the present chapter to revisit all of the policy issues where science can help to inform decision-making, but we now make a general point on the critical issues relating to the need to reconcile policy disconnects and clarify potential trade-offs that have emerged in our previous chapters (Box 6). From our perspective, a common factor in these disparate potential trade-offs is the need for more experimental and observational research to build the robust evidence base to enable evaluation and resolution.

7.3 Roles of academies

As discussed in all of the regional reports, academies of science and their regional academy networks recognise their responsibility to help mobilise research, coordinate

Box 6 Examples of public policy priorities for reconsidering and reconciling potential trade-offs for FNS

The trade-off between:

1. High-investment, high-efficiency agricultural systems (and their effect to increase trade) *and* the interests of smallholder agriculture and rural livelihoods.
2. Sustainable intensification of agriculture *and* conservation of habitat and biodiversity. Can smart sustainable intensification be achieved? There is an associated trade-off in human health: increasing agricultural productivity might harm health in various ways, through over-consumption but also by damaging ecosystems, for example by increasing pathogen habitats and disease transmission.
3. Land use for food production, bioenergy and other bioeconomy priorities *and* GHG removal, for example through reforestation.
4. Better food processing and storage, for example use of chill chain *and* increased use of energy.
5. GHG lowering by decreasing ruminant farming *and* impact of that reduction in animal production on dietary protein, vitamins and mineral intakes to meet requirements.
6. High public investment in agricultural biosciences research *and* inflexible regulatory framework that impedes uptake of that research to deliver rapid innovation.

[38] Some examples are discussed further in the recent IAP (2018) report 'Assessing the security implications of genome editing technology'.

Table 1 Roles of academies and their networks in advising on strategy and policy

Regional Academy Network	Examples of roles for academies and their networks recommended from regional reports
NASAC	Conducting and communicating findings of basic and applied research on agreed priorities. Simplifying, streamlining and focusing attention on core policy decisions by dialogue with governments and international organisations. Providing opportunities for both within- and between-country exchanges to foster mutual learning and support scaling up. Developing capacity, monitoring and evaluating progress in science-based programmes and policy. Supporting governments in achieving SDGs.
AASSA	Advising on establishment of bi-national and trans-regional research cooperation and funding mechanisms, on the basis of systems analysis and with particular regard to basic research. Identifying and advising on trans-disciplinary research priorities, and their education and extension services linkages.
IANAS	Building on presence of academies throughout the region, developing effective advocacy on evidence-based approaches to FNS. Supporting evaluation of options and action on trans-regional research initiatives and science–policy initiatives.
EASAC	Continuing role in clarifying and auditing achievements of research (including the objectives of enhanced cooperation and reduction of unnecessary competition). Establishing enduring capacity to deliver advice to policy-makers, engage with other national and international organisations and assess inter-country and inter-regional issues, emphasising that what happens within a region may have significantly wider ramifications.
IAP (from the common Foreword to all regional reports)	Facilitating learning between regions. Contributing to sharing and implementing good practice in clarifying controversial issues, developing and communicating the evidence base and informing the choice of policy options.

scientific endeavours and advise on the outputs of science to inform policy as well as to influence practice and drive innovation (Table 1).

Our recommendations for enhancing the roles of academies and their networks will be summarised in the next chapter. The remainder of this chapter focuses on options for building improved international science–policy interfaces, opportunities where academies and their networks can play a significant role. As described previously, there are specific instruments for generating international coherence in how science can advise policy, such as in harmonising principles of regulation for emerging technologies and developing transparency in food safety and standards (see, for example, Teng *et al*., 2015). However, there is also opportunity to build broader advisory frameworks. To reiterate, being receptive to and capitalising on scientific opportunities is something that should pervade policy-making widely. It is not just a matter for those involved in funding and prioritising the research agenda.

7.4 International scientific advisory groups for FNS

There are already, of course, successful examples of how experts can be brought together to assist governments in translating emerging evidence into policy-making inputs and guidance. These include, at the global level, the UN Committee on Food Security High Level Panel of Experts (CFS HLPE) and, regionally, the Malabo Montpellier Panel, discussed in detail by NASAC. The critical success factors for such activities come from the independence of the contribution, reliance on excellence in science and scientists, and sound peer review.

More is needed at the regional level. For example, AASSA recommended regional frameworks to encourage and facilitate interactions between governments, non-governmental organisations and the scientific community. IANAS observed that the modern concept of FNS sees it as embedded in a set of inter-related national, regional and global problems with multifaceted and multidimensional aspects, where effective solutions require stronger country cooperation and international integration. Regional integration is already well advanced in the EU institutions in the European region: building on this experience, EASAC advised that enhancing the science–policy interface, particularly in the context of the SDGs, requires improving efforts to reflect the diversity of international scientific insight; to exchange and coordinate between disciplines; and to promote transparency in synthesis and assessment of new knowledge in order to increase the legitimacy of recommendations to governments and society. As recommended in Chapter 5, as part of this increasing transparency and coordination it would be helpful if further international consideration were accorded to agreeing common nomenclature and definitions of terms that currently might be perceived subjectively, as controversial and liable to changing scope in consequence of advancing science, for example GMOs and precision agriculture.

The G20 policy paper (von Braun *et al.*, 2017) recommends redesigning global food and agriculture governance. One option, to support improved governance with research-based evidence, would integrate and consolidate the myriad panels and committees at international level into an International Panel on Food, Nutrition and Agriculture[39]. This model could partly follow the design of the IPCC although, to be flexible, might not need a statutory inter-governmental basis. Existing organisations and mechanisms could form the building blocks of a strengthened food and agriculture governance system—and we would welcome the inclusion of IAP on behalf of all academies of science. A new International Panel could then act to support a new international governance platform with policy clusters mapped along the set of global public policy goods (see von Braun and Birner (2017) for details).

[39] The need for an independent, international, science-based advisory group is emphasised by the historical analysis of the UN World Food Council: see http://www.nationsencyclopedia.com/United-Nations/Economic-and-Social-Development-WORLD-FOOD-COUNCIL-WFC.html.

8 Recommendations

In conclusion, on the basis of our review of the scientific opportunities and challenges in the preceding chapters, we reaffirm our starting premise that actions to tackle challenges in FNSA are relevant to many of the SDGs and to all countries. In this chapter our recommendations address the two main tasks we identified in Chapter 1: (i) to act on present scientific knowledge and data to support responsible innovation and its dissemination and improve robust policy development and coherence; and (ii) to build global scientific capacity and partnerships to identify new research priorities and close knowledge gaps.

In seeking to make our specific recommendations we first reiterate more broadly the global importance of supporting basic and well-focused applied research, their interconnections, their linkage to education and training, the concomitant needs to collect and share big data (including provision of public access) and to address impediments delaying the translation of research to innovation. Upgrading scientific infrastructure is vital but this may often be a medium- to longer-term goal. In the shorter term, we call for more collaboration between countries to share expertise and facilities and to help build capacity in emerging economies. New trans-regional research efforts are warranted, accompanied by trans-regional engagement between scientific and policy communities. Academies recognise their responsibility to help catalyse and sustain national, regional and global initiatives.

The itemised examples in the recommendations that follow are intended to be illustrative rather than comprehensive (and further examples can be found in the preceding chapters). Our scientific priorities can be broadly categorised as follows:

1. **Developing sustainable food and nutrition systems, taking a systems perspective to deliver health and well-being, linked to transformation in the circular economy and bioeconomy.**

Among the research priorities are the following:

- Understanding of the drivers of efficiency of food systems with the objective to deliver health and well-being for all populations and the planet.
- Further characterisation of the diversity of food systems worldwide—to enable capitalising on this diversity rather than advocating universal solutions.
- Measuring and modelling externalities—to understand complexity and trade-offs and account for costs (to health and environment) currently externalised in food systems and so create real cost structures.
- Developing and adopting new approaches to understanding and dealing with risk and its transmission. Partly because of new local–global connectivity, risk transmission is now more integrated across fragile systems with potential for high impact perturbation. Risk is no longer localised, but systemic.
- Clarification of issues for fair trade—how to develop equitable and resilient markets? Evaluating: non-tariff trade barriers; linkage to transboundary food safety and other regulations; impact of commodity subsidy (e.g. on availability of obesogenic diet); price volatility and the implications for access; and the correlation between local and systemic risk.
- Ensuring global coordination of food safety research and its linkage to approaches to reducing food losses.
- Exploring emerging opportunities in food science and technology for food processing—not only to reduce waste but also to widen distribution, fortify staple foods, extend seasonal availability and shelf-life, to develop healthy food structures in processed products, and enable easier meal preparation to satisfy consumer demand.

2. **Emphasising transformation to a healthy diet – How is it constituted? How is it measured? How is it delivered?**

Among the research priorities, recognising diversity in diets, are the following:

- Understanding how to influence consumer behavioural change, for example to tackle obesity. Understanding how to increase accountability in the private sector to provide healthy food choices.
- Providing evidence-based linkage of nutrition status targets with agriculture production and sustainability targets.
- Documenting health co-benefits of climate change mitigation by altering diet—quantifying implications of dietary shifts and exploring potential trade-offs between nutrition and environmental goals.
- Generating and using the evidence base to influence country-wide and population cohort-focused interventions in nutrition. Assessing implications for diet and nutrition across the life

span, for example for older people, and for other vulnerable groups.

- Improving coordination and consistency of dietary and nutritional data monitoring within and between regions.
- Evaluating health properties of hitherto neglected crops and novel functional foods—capitalising on these to diversify food systems more widely.
- Understanding implications of adopting Western-style diets in other regions—on health status and on local agriculture.
- Studying mechanisms for associations between diet-gut microbiome-disease; assessing potential for modification as part of personalised diet interventions and implications for regulatory frameworks.

3. Understanding food production and utilisation issues, covering considerations of efficacy, sustainability, climate risk and diversity of resources.

Among the research priorities are the following:

- Investigating agronomic implications and what is needed to make sustainable agriculture a priority for the bioeconomy with better integration of strategic action across sectors in pursuit of the global bioeconomy and linkage with other multi-lateral processes, in particular the SDGs and COP climate discussion actions.
- Involving economics alongside other science disciplines to evaluate new farming structures (e.g. in urban settings) and smallholder farming resilience.
- Evaluating effects of climate change on all parts of food systems and natural resources—to provide the evidence base for anticipating future impacts and creating resilience in food systems, to include climate-smart agriculture.
- Characterising agricultural properties of additional food and feed sources (including orphan crops and insects) and exploring options for making business cases for investment in novel sources.
- Exploring options for improved post-harvest practices, including processing, storage, transport and retail marketing.
- Assessing opportunities for food from the oceans/aquaculture to improve the evidence base for sustainable harvesting and culturing in marine and freshwater bodies and avoid previous mistakes of over-exploitation and environmental damage.

4. Capitalising on opportunities in the biosciences and other advancing sciences: choices should be made at the national and regional levels but on the basis of global sharing of evidence.

Among the research priorities are the following:

- Continuing to identify new ways to protect crops from biotic and abiotic stress and to promote animal health and feed conversion efficiency. This requires commitment to characterising and utilising genetic diversity and making use of the full set of plant breeding technologies available, including capitalising on new advances e.g. genome editing. Global sharing of research outputs requires better collective understanding of potential safety and security issues as well as benefits (IAP, 2018)[38].
- Clarifying evidence to choose governance options to facilitate access worldwide to the full range of science and technology advances: assessing new governance options includes the focus on regulating the product rather than the technology used in generating that product. Sharing lessons from case studies on successful application of new technology to stimulate scale up and integration of technical innovation and social innovation.
- Linking advances in biosciences with advances in digitisation and robotics to explore new opportunities in high throughput functional genomics.
- In addition to those from the biosciences, there are many other scientific opportunities coming within range. For example, use of Earth observation satellites and other sensors to collect and monitor key agronomic information and the movement of pests and diseases. There is an associated challenge to enable such information to be accessible by the research and other user communities worldwide.

5. Addressing the food–energy–water–health nexus, recognising that boundaries are blurred.

Among the research needs, to address more sustainable practices in agriculture, are the following:

- Developing scenarios for balancing food, energy, water and environment objectives, assessing validity and usability of different approaches to valuing ecosystem services and improving ability to analyse risk and opportunity in decisions about trade-offs between different ecosystem services. In particular, exploring those options for increasing agricultural production not at the expense of environmental protection.

- Addressing critical issues for food–energy linkages including the search for new local sources of energy provision in emerging economies, for example to avoid harvest losses; new opportunities to use crop waste for bioenergy; future-generation biofuels as sustainable biomass.

- Improving the evidence base to underpin introduction of practices for cost-effective soil management, improved observation systems for soil contamination, and development of techniques for soil re-carbonisation and to mitigate soil loss by erosion. There is also a promising research agenda aiming to understand functions of the soil microbiome in plant health and as a source of new products for the bioeconomy.

- Assessing air pollution, including pollution from agricultural practices such as the burning of crop residues in fields, which is also a transboundary issue that should be considered as part of the nexus and has implications for the circular economy and bioeconomy.

6. Promoting activity at the science–policy interfaces.

Addressing the scientific themes described in recommendations 1–5 will help to inform a wide range of policy actions, and their monitoring and, in turn, requires policy support to facilitate effective scientific endeavour. It is also vital that the scientific community engages with the users of research and the public-at-large, including involving them in strategic decisions about planning research.

Our recommendations for policy support to enable these relationships include policies for the following:

- Making research results globally available, requiring a plurality of mechanisms for collaboration and technology transfer.

- Achieving consensus on what is an appropriate level of research allocation for FNSA.

- Investing in human resource development, building capacity in education and training with linkage to new employment options, extension services, and curricular reform to promote multi-disciplinary collaborations and infrastructure that includes centres of excellence.

- Stimulating international cooperation in science, technology and innovation: developing, sharing and implementing frameworks for incentivising science and dealing with complexity.

- Offering new incentives for public–private partnerships to improve human health and well-being and planetary health.

- Continuing to reform trade, subsidies and property rights, to be compatible with other policy actions on agriculture, health and the environment.

- Sharing evidence to inform and develop robust but flexible, proportionate and transparent regulatory frameworks for emerging technologies.

- Using robust data to develop coordinated ways to reduce food loss and waste.

- Agreeing international standards on antibiotic use in agriculture, with monitoring of implementation of standards and assessment of impact on human health.

- Promoting use of data for diverse purposes, many described in previous chapters but also including, for example soil testing and weather forecasting.

7. New international science advisory mechanism.

Our priorities for research and policy also encompass the strategic priority for consolidating, coordinating and developing more effective ways to reach both policy-makers and the public with our key messages. The work required to develop and maintain a coherent policy framework warrants further attention to be given to constituting an international advisory panel on FNSA, to include participation by academies and serving to strengthen international governance mechanisms.

8. Actions to be taken by member academies of IAP.

Various academy roles were discussed in Chapter 7 and it is now important for IAP and the regional academy networks to encourage academies to take a lead in implementing recommendations 1–7. This requires augmented communication by academies at the forefront of the scientific community, acting as sources of advice, independent of vested interests and participation in strengthening the evidence base (knowledge and data), integrating information from multiple disciplines and sectors. Academy responsibilities include the following:

- International advisory roles: supporting existing strategic collaborations, for example between AU and EU, G7, G20, and promoting the sharing and use of information in new international initiatives, in particular the proposed International Advisory Panel on Food And Nutrition Security and Agriculture. More academies should be more proactive internationally in promoting evidence-based policy decisions and helping to evaluate the impact of those decisions.

- Academy science policy advisory capacity-development: sharing knowledge and expertise between academy networks to build capacity at the science–policy interface for newer and smaller academies.

- Auditing progress in science and innovation: monitoring, assessing and, where appropriate, highlighting science and technology developments, including providing clarification on new and emerging technologies.

- Science and technology capacity-building: contributing to building science and technology capacity and critical mass in countries and regions. Academies can help to enhance collaboration within the public sector and between the public and private sectors, including technology transfer.

Our recommendations aim to augment momentum at the science–policy interfaces worldwide. It is imperative to impel new global coordination and coherence. As observed by IAP in the common Foreword to all the regional reports on FNSA: '*The Sustainable Development Goals provide a critically important policy framework for understanding and meeting the challenges but require fresh engagement by science to resolve the complexities of evidence-based policies and programmes.*'

We close by reaffirming two conclusions. Collectively, there is need to be more ambitious in identifying the scientific opportunities for sustainable and healthy diets. And, food systems are in transition: living within planetary boundaries (including those for nutrients, water and climate) and having healthy populations requires new approaches to food systems. There is need to build critical mass in research, teaching and innovation and to mobilise those resources in engaging with policy-makers and other stakeholders.

Appendix 1 Preparation of the IAP global report

This report draws on the published outputs of the four regional working groups (AASSA, EASAC, IANAS and NASAC) together with involving experts from these working groups, in collective discussion, in Germany in April 2017 and Jordan in November 2017.

An initial draft of the text was prepared by Robin Fears with the assistance of Claudia Canales on behalf of the IAP project scientific secretariat in conjunction with a small editorial group and was further revised after a review meeting in Halle, Germany, 12–14 February 2018. This expert editorial group comprised the following members:

Volker ter Meulen and Joachim von Braun (Germany, Co-Chairs)
Tim Benton (UK)
Eduardo Bianchi (Argentina)
Christiane Diehl (Germany)
Mohamed Hassan (Sudan)
Sheryl Hendriks (South Africa)
Elizabeth Hodson de Jaramillo (Colombia)
Molly Hurley-Depret (Luxembourg)
Lyunhae Kim (Republic of Korea)
Yoo Hang Kim (Republic of Korea)
Krishan Lal (India)
Jeremy McNeill (Canada)
Paul Moughan (New Zealand)
Jackie Olang-Kado (Kenya)
Jutta Schnitzer-Ungefug (Germany)
Aifric O'Sullivan (Ireland)
Katherine Vammen (Nicaragua)

In addition, written feedback was obtained in discussion with Michael Clegg (USA) and Adriana de la Cruz Molina (Mexico).

The text was reviewed by the regional academies' networks and endorsed by the IAP.

Appendix 2 Characteristics of the current global status of FNS analysis—and the research implications

Source	Key messages
UN Secretary-General Scientific Advisory Board 2016 'Food Security and Health Policy Briefing'	Invest in science, technology and innovation with new interdisciplinary and food systems approaches, recognising interrelationships between food-nutrition-health. Global effort requires human and institutional capacity building accompanied by public–private partnerships and equitable trade and business to support economic growth. Global food security must be aligned with climate-smart sustainable production systems and other action for stewardship of natural resources.
FAO multiple publications including 2016 'Status of Food and Agriculture' and 2017 'Future of Food and Agriculture: Trends and Challenges' in preparation for FAO medium-term plan 2018–2021.	Describes driving forces of economic growth and population growth in promoting agricultural demand and dietary transitions. Although hunger and extreme poverty globally have been reduced since the 1990s (but see FAO *et al*. (2017) for more recent analysis), climate change disproportionately affects food insecure regions and conflicts, crises and natural disasters are increasing in number and intensity. Food systems are becoming more capital-intensive, vertically integrated and concentrated in fewer hands. These trends challenge sustainable production and resilience, and rethinking of food systems and governance is essential. All countries are interdependent on the path to sustainable development and collective responsibility requires fundamental change in production and consumption.
WHO 2017 'Ambition and Action in Nutrition 2016-2025'	Nutrition is now on the top priority list of WHO, aiming to leverage changes in relevant non-health sectors to improve and mainstream nutrition. WHO will work to define healthy, sustainable diets and guide the identification and use of effective nutrition actions, including improving their availability in health systems, supported by establishment of targets and monitoring systems for nutrition.
IFPRI multiple publications including 2016 'Global Nutrition Report', and 2017a Global Food Policy Report	The documents provide another comprehensive overview of the state of FNS. Recommendations focus on how to develop a food system that is inclusive, climate-smart, sustainable, efficient, nutrition- and health-driven and business-friendly. The Global Nutrition Report concentrates on the theme of making and measuring specific, tangible commitments and assessing what it would take to end malnutrition in all its forms by 2030. It is emphasised that current public spending commitments do not match the need. Recommendations are to make the political choice to end all forms of malnutrition; invest more and allocate better; fill data gaps; implement evidence-informed solutions; and conduct research to identify new solutions. IFPRI (2017a) notes the impact of the worsening of the refugee crisis and natural disasters and provides emphasis on the effects of urbanisation on food systems. Additionally, there is a discussion of other relevant international and regional development groups, for example G20, G7, African Development Bank Group Strategy for Agricultural Transformation and the African Green Revolution Forum.
Food Security Information Network 2017 'Global Report on Food Crises'	Review of most severe problems of food insecurity in 2016, increased from 2015, and exacerbated by conflict, record high food prices and abnormal weather patterns caused by El Niño. In some cases, crises affected entire national populations and spill over effects had significant impact on neighbouring countries. Outlook in 2017 indicates worsening conditions in some locations, which may engender famine.

Source	Key messages
Global Panel on Agriculture and Food Systems for Nutrition, Haddad *et al*., 2016 (see also series of policy briefs on http://www.glopan.org)	Recommendations for new global research agenda to focus on nutrition are wide-ranging and go beyond agriculture to encompass trade, environment and health, harnessing power of the private sector and empowering consumers to demand better diets. Recommendations include the following: (i) Identify where to intervene in food systems. (ii) Share data analysis more widely. (iii) Evaluate what constitutes a healthy diet, for example dose–response relationships. (iv) Tackle all forms of malnutrition simultaneously. (v) Understand aspects of food processing, transport and other elements of the food system on diet. (vi) Develop better mechanisms for public–private interactions to shape and implement research priorities. (vii) Identify co-benefits for climate change mitigation and health. (viii) Promote nutrition-sensitivity in all aspects of supply and demand, for example crop breeding programmes. (ix) Identify economic levers for change in food systems, for example at policy and regulation levels. (x) Develop metrics to understand economic externalities of individual and government choices on diet.
CGIAR Strategy and Results Framework 2016-2030, 2015	Research priorities include the following: climate-smart agriculture; genetic improvement of crops; nurturing plant and farming system diversity; natural resources and ecosystem services; gender and inclusive growth; nutrition and health; agricultural systems; and enabling policies and institutions.
World Bank Agriculture and Food on http://www.worldbank.org/en/topic/agriculture including 2016 paper 'Future of food: shaping the global food system to deliver improved nutrition and health' and 2017 paper 'Future of food: shaping the food system to deliver jobs'	Another comprehensive coverage of research needs and opportunities, in particular for food security; climate-smart agriculture; food system jobs; and food quality and safety.
Various reports from UN Committee on World Food Security High Level Panel on Food Security and Nutrition (HLPE) (http://www.fao.org/cfs/cfs-hlpe/en/) and Critical and emerging Issues in Food Security and Nutrition, 2017, (http://www.fao.org/cfs/cfs-hlpe/critical-and-emerging-issues/en/)	(i) Climate change and natural resource management (ii) Nutrition and health (iii) Food chains (iv) Social issues (v) Governance (vi) Knowledge and technology

Appendix 3 IAP template

The overall goal for the IAP project is to show how science can be engaged to promote and support FNSA. This goal encompasses both (i) the better use of the scientific evidence already available to inform policy options and stimulate innovation and (ii) the identification of knowledge gaps in order to advise on research priorities to fill those gaps and improve the evidence base for public policy and resource for innovation.

Thus, the criterion for identifying which particular topics to cover is primarily 'scientific opportunity' within the context of the IAP project objective to add value to work already done by others. The initial collective scoping work of the four regional academy networks has been synthesised into the following 10 questions and there will be many linkages between these top-level themes. The 10 top-level questions are intended, as the shared starting point, to help inform the framework for each regional academy network Working Group. This does not mean that each regional output needs to conform to a uniform structural format but rather that the issues raised and key messages delivered from all four Working Groups can be subsequently mapped onto the agreed top-level themes, to serve as the resource for the IAP global-level phase. Individual bullet points listed within each of the 10 themes are not intended to be comprehensive or mandatory but illustrative of some specific issues that may be addressed. There will, of course, be others according to the particular evidence reviewed and expertise employed within each region.

1. **What are key elements to cover in describing national/regional characteristics for FNSA?**

- Definitions and conceptual framework for FNSA including: how measured, links with health, and covering demand-side as well as supply-side issues to assess overall current 'fitness for purpose' and clarify boundaries for framing the themes.
- Including status and standards for population groups (variation within region, demographic, vulnerable).
- Covering excess consumption as well as undernutrition.

2. **What are major challenges/opportunities for FNSA and future projections for the region?**

- Climate change (impact of climate change on FNSA and contribution by agriculture to climate change).
- Population growth, urbanisation, migration.
- Supply instabilities and others (e.g. political, economic, financial).
- Ensuring sustainability (environmental, economic, social), and building resilience to extreme events (e.g. to address increasing systemic risk from interruption of increasingly homogenous food supplies).
- Agriculture and food in the bioeconomy.
- Scenario building.

3. **What are strengths and weaknesses of science and technology at national/regional level?**

- Relevant cutting-edge capabilities: including social sciences, inter- and trans-disciplinary research, modelling.
- Opportunities and challenges for research systems in context of tackling major vulnerabilities in FNSA; relative contributions from public and private sectors.
- Handling and using big data in food and nutrition science/open data opportunities.
- Issues for mobilising science and deploying outputs from research advances, addressing innovation gaps and ensuring next generation of researchers, farmers, etc.
- Science–policy interfaces. Sharing science within the region.
- External (indirect) effects—impact of research and innovation in the region on outside the region.

4. What are the prospects for innovation to improve agriculture (e.g. next 25 years)—at the farm scale?

- Issues for societal acceptability.
- Plants (e.g. plant breeding, ensuring genetic diversity).
- Animals (e.g. advent of genome editing).
- Tackling pests and diseases.
- Food safety issues.
- Agronomic practices (e.g. precision agriculture).
- Not just terrestrial—also use of aquaculture/marine resources, developing market potential while avoiding over-exploitation and depletion of genetic diversity.

5. What are the prospects for increasing efficiency of food systems?

- Understanding the agricultural/food value chain and institutional frameworks so as to characterise issues for the integrative food system.
- Issues for food utilisation and minimising waste (including during harvesting, processing, consumption stages).
- Tackling governance/market/trade issues to ensure affordable food and minimise market instability.
- Food science issues. Food retail issues.

6. What are the public health and nutrition issues, particularly with regard to impact of dietary change on food demand and health?

- Characterising current trends in health related to issues for FNS.
- Issues for expected changes in consumption patterns (and implications for food importation); understanding and incentivising behavioural change, emerging personalised nutrition.
- Innovative foods and new food sources.
- Food safety issues.
- Promoting nutrition-sensitive agriculture to provide healthy and sustainable diet with connected issues for resource use and food prices.

7. What is the competition for arable land use?

- Impacts of urbanisation (including issues for agricultural labour force and new opportunities in urban agriculture as well as issues for available arable land).
- Bioenergy and other bioeconomy products.
- Multifunctional land use—goals for biodiversity and ecosystem services.
- Potential for expanding arable land availability (e.g. from marginal land).
- Implications of forestry trends.
- Also competition for resources with regard to marine sustainability.

8. **What are other major environmental issues associated with FNSA—at the landscape scale?**

- Contribution of agriculture to climate change.
- Intersections with other natural resource inputs (water, energy, soil health) and fertilisers/other chemicals. Irrigation issues in multi-use water systems. Wastewater.
- Balancing goals for sustainable development and FNSA.

9. **What may be the impact of national/regional regulatory frameworks and other sectoral/inter-sectoral public policies on FNSA?**

- Policies that foster technological innovation.
- Policies that build human resources (e.g. education, gender, equity).
- Policies that redesign whole agricultural ecology (land use, bioeconomy, etc.).
- Policies to promote consumption of healthy food.
- Issues for policy coherence.

10. **What are some of the implications for inter-regional/global levels?**

- Link with global objectives, for example SDGs and COP 21—issues for their scientific underpinning and resolution of conflicting goals.
- Wider impact of national/regional policy instruments e.g. trade, development policies.
- International collaboration in FNSA research and research spillovers.
- International FNSA science governance infrastructure and science advisory mechanisms.

Appendix 4 Collated list of recommendations from all four regional reports

The material collated in this Appendix is derived from each of the regional report summaries.

NASAC

NASAC (2018). Opportunities and challenges for research on food and nutrition security and agriculture in Africa. On On http://nasaconline.org/wp-content/uploads/2018/05/NASAC-FNSA-Opportunities-and-challenges-for-research-on-food-nutrition-security-and-agriculture-in-Africa.pdf

The following priorities are highlighted as illustrations of how scientific enquiry can generate information for evidence-based policy, and advance and support transformation of the African agricultural sector and food system to improve food security and reduce malnutrition in Africa.

1. Strong political commitment informed by scientific evidence

- Achieving Africa's ambitious growth and development agenda as set out in Agenda 2063 and the Malabo Declarations will require well-informed informed policies and action plans, the appropriate institutional arrangements, capacity at all levels and the requisite funding. This will necessitate strong investment from African governments and their funding partners along with the active partnership of the private sector and international research centres.

- Governments should take responsibility for directing this transformation and provide opportunities for the closer engagement of researchers and policymakers for mutual learning and benefit.

- Strategic cooperation in the form of research alliances and partnerships could include the establishment of multi-sectoral and multi-institutional science, technology and innovation (STI) platforms as part of national food and nutrition systems for peer review, mutual learning and mutual accountability in line with Malabo Declaration commitments to improve policy and programme alignment, harmonisation, and coordination. Multi-sectoral institutional platforms and arrangements can mitigate the challenges of low investment, brain-drain, brain-wastage as well as the fragmented and expensive duplication of efforts.

- Closely monitoring land use change and determining its impacts on food security at different levels – national, community and household – is necessary to protect household food security and ensure that these investments do not degrade the natural environment and that they lead to inclusive economic growth and viable employment opportunities—especially for women and youth.

- Advancing ICT to support multi-sectoral big data platforms with the necessary capacity could support on-going monitoring and evaluation of policies and programmes as well as the efficiency of the agriculture and food systems. This will inform policies and actions and document the impact of these for mutual learning and refinement of development actions.

2. Agriculture and food system efficiency

- Ensuring quality and sustainable supply of seed and vegetative propagation materials of indigenous and underutilised foods will increase production of these foods, making them more available to consumers. National research systems must support these actions. More investment is necessary to collect and categorise orphan crops and wild populations. Modern molecular breeding technologies offer potential to preserve these resources and increase their availability.

- Researching how to improve the efficiency of livestock and aquaculture rearing and feed quality is equally important for FNS in Africa.

- Advances inappropriate modern technologies, biotechnology and biosciences can provide timely and efficient management of biotic and abiotic factors that limit agricultural productivity and nutrition.

- Applying modern breeding technologies could improve and enhance the diversity and utilisation of indigenous and underutilised foods in Africa.

- Researching to find solutions that reduce the drudgery in Africa's largely un-mechanised farming and food systems can improve equality. This is essential for freeing up women's' time in particular.

3. Farming system resilience

- Improving mixed farming systems could improve food productivity amidst greater levels of uncertainty. This could improve prospects for smallholder livelihoods and environmental protection.

- Stakeholders (including farmers) need to work together to improve the resilience of farm systems through climate-smart agriculture approaches. These require supportive public policies and context-appropriate programmes supported by research and development, well-qualified extension staff as well as knowledge and technology transfer on a large scale.

- Monitoring changes in the environment through the soil and water mapping can support agricultural production decisions at all levels. Getting this information into the hands of African farmers via ICT applications to support decision-making is essential.

4. Food system efficiency, human health and well-being

- STI research can find ways to promote product diversification with nutritious foods; processing to extend shelf life and make healthy foods easier to prepare and improved storage and preservation to retain nutritional value; ensure food safety; extend seasonal availability and reduce post-harvest losses (including aflatoxin) and food waste. These solutions should consider current changes in demand, predict future demand changes and shape the future of the African food system in ways that will provide nutritious food for all.

- Develop processing and packaging technologies to respond to consumer demands for safe and healthy alternative foods and extend the shelf life of foods. The limitations of water and power supplies need to be considered in developing these technologies.

- Increasing funding for more research into the fortification, biofortification and enrichment of foods can increase the nutritional value of commonly consumed foods, improve the bioavailability of nutrients for absorption and metabolism or decreasing the concentration of anti-nutrient compounds that inhibit the absorption of nutrients (e.g. phytates and oxalates). A focus on harnessing the inherent properties of indigenous knowledge and foods is needed.

5. Food safety and waste reduction

- Developing technologies to overcome the shortage of cold storage and refrigeration in Africa is necessary, including innovation in processing and packaging to ensure stable, safe foods, particularly in areas where electrification levels are low. The use of solar energy is one possible area to explore.

- Strengthening and enforcing agriculture and food regulations and standards and building the requisite capacity (human, technological and infrastructure) will ensure food safety and ensure access to export markets.

- Research and training can reduce the risks and hazards associated with the over-use of agricultural chemicals.

- Alternative approaches and techniques can reduce the need for chemicals that are harmful to environmental, human health and well-being, yet are affordable and accessible to farm households in Africa.

- Empowering farmers to monitor and control the spread of diseases and pests and enhancing the capacity of farmers with information on digitised soil, weather, cropping and disease information systems to take vital decisions and actions at the farm level.

- Conducting epidemiological research to establish patterns of contamination and health effects of mycotoxins in Africa can inform better management and containment of these risks. This needs to be complemented with building more capacity to test and certify products; develop innovative and cheaper testing methods (including rapid digital assessments) and step up the enforcement of minimum quality standards in food products through innovative cost-sharing practices.

6. Human capacity

- Strengthening the human and infrastructural capacity for agricultural research, innovation and technology will support transformation. African academic institutions must work to develop food security and nutrition capacity at all levels of society and across traditional disciplines. Increased effort is required to ensure a well-trained extension service that is constantly updated.

- Providing support and incentives to the stakeholder in the agricultural sector to mentor youth involved in value addition within the context of economic growth, food security and poverty alleviation will assist in addressing unemployment and bringing young people into the sector. Empowering the youth with appropriate skills and mainstream gender in FNS programmes in partnerships with training institutions, business sector and civil societies will take deliberate actions on the part of all stakeholders.

AASSA

AASSA (2018). Opportunities and challenges for research on food and nutrition security and agriculture in Asia. On On http://aassa.asia/achievements/achievements.php?bbs_data=aWR4PTE0MCZzdGFydFBhZ2U9MCZsaXN0Tm89JnRhYmxlPWNzX2Jic19kYXRhJmNvZGU9YWNoaWV2ZW1lbnQmc2VhcmNoX2l0ZW09JnNlYXJjaF9vcmRlcj0=ll&bgu=view

Recommendations

1. A strategy moving forward would be to undertake systems analysis to identify key impediments to raising food yields or supplying an adequate balance of food types. The systems analysis would prioritise extension, education and R&D needs, region by region and/or group by group, and would provide guidance on means of sustainably increasing food production and diversity. There will undoubtedly be some R&D/extension/education focus areas that are of global relevance and are universally applicable.

2. Priority in relation to R&D and educational efforts should be given to countries and regions that have been identified as at 'high risk' concerning current and future FNS. Particular focus should be afforded to India, Bangladesh, Pakistan, Afghanistan, Nepal, Myanmar (countries having elements in common), the Philippines, Iraq, Tajikistan and Yemen.

3. Consideration should be given to the effects of different age distributions in future populations, with respect to dietary types and nutritional needs as related to FNS.

4. Any consideration of future FNS should consider not only the production of more food calories and nutrients (to combat potential undernutrition), but also the production of a wider diversity of food types and strategies to prevent obesity and its associated non-communicable diseases.

5. Work should be undertaken in countries and regions at 'high risk' of future FNS, at a more localised provincial and sectoral level, to generate data to allow a better understanding of FNS and its drivers.

6. Scientific evidence juxtaposed with advanced assessment analyses should inform and influence policy options. To ensure and further encourage the involvement of scientists in policy decisions, at the national and regional levels, regional frameworks that encourage and facilitate interactions between government, non-governmental organisation policy-makers and scientists should be initiated.

7. The IAP should convene an expert panel to determine an agreed-upon nomenclature for use in describing crops developed through biotechnology techniques. Genetic modification is a natural process, and there is confusion with the current terminology.

8. Policies at both national and regional levels within Asia/Oceania should be developed, to form multi-disciplinary science and technology collaborations to target specific outcomes.

9. Common impediments to increasing FNS at national, regional and local levels should be identified and evaluated, along with generic over-arching technologies, to form a blueprint for future Asia/Pacific FNS R&D.

10. The AASSA should work with its constituent societies to develop a trans-national funding mechanism that puts *basic research* connected to FNS at the forefront. Such a framework, if properly funded, can have far-reaching

consequences for both science and technology and FNS in the Asia/Pacific region, similar to the effect of the European Research Council integration grants on science in Europe.

11. The AASSA should work with its constituent societies to further develop binational research cooperation in FNS.

12. Considering the R&D lag between investment and adoption/return on investment for agricultural and food research, national governments should not only maintain support for basic R&D but also increase overall levels of funding (as a percentage of GDP) for FNS.

13. There should be research effort to understand the holistic nutritional and health properties of individual foods and mixed diets, so as to better define the characteristics of a healthy diet.

14. Ultimately food types and diets that are both healthy and socially and culturally acceptable should be defined at a local level, taking into account a wide diversity of views and beliefs.

15. The food science and technology, nutrition and plant/animal breeding disciplines should work together to develop functional foods containing high natural levels (or following fortification) of health-enhancing bioactives as well as minerals and vitamins. Such functional foods should be targeted constituents of healthy diets.

16. There should be better education concerning the role of food and nutrition in health, and such education should occur at all levels of the education system and should be generic. There should be specialised training for health professionals, including doctors and other primary influencers. The role of dieticians in communities should be expanded.

17. Reliable data on food wastage and how it varies with the food production system and with socio-economic sectors of a population need to be generated, and strategies to minimise food wastage need to be devised.

18. Valid metrics and measurement mechanisms and approaches to enable practical descriptions of sustainable farming systems and sustainable diets should be developed, to allow a complete evidence-based assessment of sustainable diets.

19. Efforts to collect, phenotype, catalogue and preserve diverse wild relatives and landraces of cultivated crops should be extended. In particular, efforts must go into advanced high throughput phenotyping and genotyping technologies.

20. Research efforts, including new target identification studies, to further develop CRISPR–Cas9 and similar NBTs for use in crops should be enhanced. Regulations should be evidence based and, where supported, NBTs should be classified as non-genetically modified.

21. Research into developing new feedstuffs (lower down the food value chain) for simple-stomached animals (e.g. pigs, poultry and fish), and into the underlying mechanisms of productive efficiency, is urgently needed. Research into pasture-based systems for ruminant production and the mitigation of GHGs should be a priority. NBTs and new reproductive technologies need to be properly assessed on the basis of scientific evidence and, where found to be acceptable, should be pursued vigorously.

22. Interdisciplinary research among engineers, geographic scientists, biologists and data scientists to develop better-integrated sensing and reporting systems and to promote precision agriculture and robotics should be encouraged.

23. Impact analyses to identify and overcome impediments to adopting precision agriculture systems among small scale farmers should be encouraged.

24. New scalable insect and algal species for use in the food industry and alternative animal feeding systems should be identified. Studies into algal chemistry pre- and post-extraction and the identification of novel chemistries should be encouraged.

25. Further adoption of aquaculture technologies through research into intensified growth conditions and the identification of new species should be promoted.

26. Specific food security research calls in aquaculture, which will attract scientists in other fields (e.g. virologists and engineers) to pursue relevant research, should be encouraged.

27. Investment in interdisciplinary R&D relevant to FNS in Asia/Oceania needs to be increased significantly. Consideration should be given to forming cross-nation, cross-disciplinary consortia (centres of research excellence), to focus on defined pressing issues related to FNS.

28. Regional cross-nation initiatives should be implemented to greatly increase the quantum of education and training of the next generations of scientists, technologists, extension officers and leaders in agriculture, nutrition and food. Training should have a trans-disciplinary basis.

29. The implications of the use of land for non-food crop production (including for clothing and biofuels), urbanisation and industrial expansion for FNS and the preservation of biodiversity need to be better understood and reflected in policies and planning.

30. The rapid change in the world's climate introduces considerable uncertainty and risk for future world food production. The recommendations of the main international climate agreements, including Paris 215, the Sendai Framework for Disaster Risk Reduction 2015–2030 and the United Nations SDGs 2015, need to be addressed. Means to mitigate these risks in the Asia/Pacific region should be a priority.

31. Water and soil use management (and the contamination of water, soil and food with fertilisers, herbicides and pesticides) needs to be an integral part of any strategy to increase food production. Sustainability of production must be to the fore.

IANAS

IANAS (2018). Opportunities and challenges for research on food and nutrition security and agriculture in the Americas. On: https://www.ianas.org/docs/books/Opportunities_challenges.html.

The major findings of the assessment of FNS in the Americas are presented below.

1. **Owing to an exceptional abundance of natural resources, the Americas are a privileged region. The region's wealth in agrobiodiversity, arable land and availability of water, all constitute major advantages for the future.**

- The Latin American region is a biodiversity superpower that includes five of the ten most biodiverse countries in the world.
- Latin America is the largest net food exporter in the world, yet 18 countries in Latin America and the Caribbean are net food importers.
- North America is the second largest net exporter.
- Aquaculture has emerged as a major industry in countries such as Canada, Chile, Mexico, Peru, Argentina and Ecuador.
- More than 85% of all biotech and genetically modified crops are currently planted in the Americas, which have provided substantial environmental benefits through reduced herbicide use, low or non-tillage practices, increased productivity per unit land area and reduced GHG emissions.
- The region of the Americas has major potential for growth in food production.

2. **There is substantial diversity among national agricultural research systems, infrastructure, investments in human capital, in financing capabilities and in the roles of public and private sectors in the provision of STI. Some critical issues include the following.**

- While STI capacity is substantial among large countries in the Americas, it is less well developed in many smaller countries, making regional cooperation especially important. In almost all countries, universities are crucial in training human capital for food systems and are key sources of research and innovation.

- There has been a long-standing practice of supporting international exchange in graduate education for agriculture and related subjects, but participation by the USA has declined, while increasing opportunities in Brazil and various European countries have, in part, compensated. In general, these exchange practices are not formalised into international governmental agreements and access to infrastructure and financial support varies greatly among countries.

- Broadly speaking, collaboration between universities and research centres is not robust, so it is important to create more stable and dynamic links. The CGIAR centres such as CIAT (International Center for Tropical Agriculture, Colombia), CIMMYT (International Maize and Wheat Improvement Center in Mexico), and IICA (Inter-American Institute for Cooperation on Agriculture, Costa Rica) stand out as an exception by connecting agricultural research throughout Latin America and the world.

- Public investment is essential for agricultural research in all the countries of the region. However, in many countries in the Americas, investment is far below the average of the most developed countries and even below those recommended by organisations such as the United Nations.

- Many countries do not have adequate databases for characterising the status of their agricultural system and there is insufficient statistical information on the sector.

- The nations of the Americas are not very integrated with respect to agricultural trade and economic policies. A valuable first step is the regional network of public food supply and marketing systems for Latin America and the Caribbean to promote inclusive and efficient production and marketing created in 2015 by Brazil, Bolivia, Chile, Costa Rica, Ecuador and Saint Vincent and the Grenadines, but more needs to be done.

- There are very few private companies in the field of agriculture or agricultural biotechnology with their own research programmes in most of the countries in the region. The USA, where approximately 60% of the agricultural research investment comes from the private sector, is an exception. Canada follows with roughly 12% of private sector investment.

- Effective collaboration networks between research centres and private companies are crucial, so that efforts in science and technology are focused on solving problems related to the needs of the productive sector.

- In many countries, the link between scientific research and the FNS needs of vulnerable populations is weak.

- Reducing food waste and loss is a joint task in which all actors – producers, distributors, retailers, consumers, research institutions and governments – must intervene decisively.

- The identification and correction of the substantial weaknesses in the agri-food systems of many countries in the Americas constitute an urgent agenda that can be most efficiently pursued within an interregional cooperative framework.

3. The efficient use of water resources is essential for future growth in food production, public health and quality of life in the Americas.

- Poor water quality and inefficient water management are among the greatest environmental challenges for the Americas. The Americas are rich in water resources, but STI-based improvements for water management, especially with respect to optimising irrigation efficiency, are essential to meeting the food producing potential of the region.

- Periodic droughts exacerbate water management problems; years of high rainfall lead to over-use, followed by economically painful contractions in lean years.

- Water quality is increasingly degraded by unwanted contaminants, including pathogens, fertilisers, pesticides, decomposed plant material, suspended sediment and other contaminants such as fuels and solvents. Runoff into streams and lakes causes turbidity that is harmful to fish and adds materials that, over time, reduce the volume of lakes and reservoirs. Eutrophication of surface waters due to agricultural inputs such as phosphorus and nitrogen is a continuing problem.

- The focus is shifting from land productivity to water productivity, which requires changes in cropping patterns, innovative irrigation approaches, crop improvement strategies, novel policies and greater investment in research and capacity development.

- Institutions and protocols need to be developed and implemented for groundwater management. Groundwater resources are important as buffers to drought and supplements to surface supplies. There are many instances throughout the Americas where groundwater resources will be prematurely depleted if left unmanaged.

4. **Water, food and energy are interdependent resources that need more integrated management.**

- It is important to identify the energy forms that use large amounts of water and to gradually replace them with ones with the potential to reduce water use.
- Innovations in solar and wind energy production have almost no impact on water.
- The water requirements used to irrigate crops grown for biofuels can be much larger than for the extraction of fossil fuels. Biofuel-based subsidies that incentivise farmers to pump aquifers at unsustainable rates have led to the depletion of groundwater reserves and such practices must be discouraged.

5. **The region of Latin America continues to suffer massive deforestation and associated environmental degradation. The largest net losses (3.6 million hectares per year) were recorded between 2005 and 2010 and occurred in South America.**

- In all countries, the conversion of forests to farmland increases erosive processes and has an extremely negative impact on water bodies and riparian zones, owing to higher rates of sedimentation, eutrophication and reduction of the regulation capacity of the hydrological regime, leading to higher risks for flooding intensity. Deforestation is also a major cause of GHG accumulation and therefore a driver of climate change.
- Most areas of the Americas are facing great challenges related to the destruction and fragmentation of habitat. This is caused by the expanding agricultural frontier, urbanisation, tourism and other land and commercial developments, together with changing consumption habits.
- Deforestation in many areas of the Americas has a high impact on quality of life especially for poor and rural populations.
- Deforestation has multiple economic and social drivers including (1) population growth, (2) land use changes (spread of the agricultural frontier), (3) unsustainable economic expansion, (4) poverty and (5) corruption.

6. **Climate change research is essential, not only because agriculture is a major source of GHGs, but also to develop strategies for climate adaptation and mitigation in every country.**

- The abundance, incidence and severity of pest and disease attacks is one of the major predictable threats of climate change.
- *In situ* and *ex situ* preservation of local genetic resources is an important insurance policy against climate change.
- The Caribbean is particularly vulnerable to environmental degradation and at the greatest risk of climate related disasters. The Caribbean is also the most vulnerable region for FNS, because it is heavily dependent on imports and suffers from a weak, undiversified economy. More attention must be focused on the special needs of the Caribbean region.
- A focus on average climate statistics obscures the fact that it is the extreme events that cause most damage. It will be important to manage for extreme events and to recognise that what were once believed to be 100-year events are now more likely to be decadal or even more frequent. Strategies to minimise risk will become essential tools.

7. **A key future challenge is to produce more healthy food without increasing agricultural area, while simultaneously reducing GHG emissions and reducing wastage.**

- On the basis of the ranking of 25 countries in the 2016 Food Sustainability Index (including measures of food waste, sustainable agriculture and nutritional challenges), the countries in the Americas that were ranked occupy mid to low levels: Colombia 10, USA 11, Argentina 14, Mexico 15, and Brazil 20. This suggests that there are substantial opportunities for further improvement in the Americas.

- An important step forward will be the adoption of the circular economy model of reducing, reusing and recycling in production. This model should promote sustainability and encourage the process of value addition for products such as processed foods, probiotics, prebiotics, nutraceuticals, bioenergies and biomaterials, thereby strengthening and diversifying local economies.

- Modern technologies, such as biotech crops and precision agriculture, are critical to producing more healthy food without increasing agricultural acreage, while at the same time reducing GHG emissions and wastage.

- However, the adoption of modern technologies is slowed by constraints on infrastructure that are common to all countries in the Americas. These constraints include the development of adequate irrigation systems, adequate water and food storage capacity, sufficient transport and road systems, and adequate investment in STI-producing institutions.

- Big data and modern information technology offer substantial opportunities to advance sustainable management practices. These approaches can be especially valuable in anticipating and mitigating climate related impacts, enhancing water use efficiency and improving agricultural efficiency.

8. **Malnutrition, food insecurity and obesity coexist to a greater or lesser degree, as well as chronic diseases related to obesity.**

- In several countries in the Americas, a reduction in poverty and malnutrition over the past 10 years has been associated with an increase in obesity. Thus, poverty reduction is a necessary, but not a sufficient condition for adequate, healthy diets.

- NCDs represent the main cause of morbidity and mortality in the USA, Argentina, Uruguay and Chile and impose heavy costs on healthcare systems.

- More behavioural research is needed to determine how food choices are made and how they can be modified, together with a more rapid assimilation of science-based best practices into the food production system.

- It is crucial to recognise, and incorporate into policy, the key role gender plays in food production, food preparation, food selection and nutrition.

- There is a strong need for more effective systems for water purification and distribution. Safe drinking water remains an important issue in the Americas and has a clear link with the incidence of food-borne disease.

9. **Progress in the Americas over the past quarter of a century has been impressive and STI has played a major role in improvements linked to the Millennium Development Goals. STI will continue to play a key role in achieving the SDGs by 2030, but progress will depend in part on greater regional and global cooperation in STI and partly on the development of more uniform policy frameworks.**

- STI is essential, not only to achieving FNS, but also to eradicating poverty, protecting the environment and accelerating the diversification and transformation of economic conditions.

- Agriculture is increasingly seen as a dynamic sector, driven by STI, for the transformation of national economies in the future. However, it will be important to generate an enlarged framework for STI cooperation and coordination in the Americas with respect to FNS.

- Past investments in agricultural research have yielded high returns (estimated at 20- to 40-fold globally), but rates of gain are now declining as the potential of older technologies (e.g. the Green Revolution) are fully exploited. A whole suite of new technological innovations shows great promise for future plant and animal improvement. These new innovations include more efficient use of water and nutrients, increased yields, more effective approaches to pests and diseases, the integration of robotics with big data and advanced algorithms for more efficient management, and the adoption of best practices in agriculture. It will be important to accelerate the rate at which promise is turned into practice.

10. **STI alone cannot achieve all the advances in FNS required for the future. STI advances, combined with effective evidence-based policy, must be implemented more widely in the Americas.**

- It is hard to overemphasise the importance of governance and public policy in achieving both FNS and in supporting the development of more sustainable agricultural policies. One only needs to consider the present situation in Venezuela where an otherwise well-endowed country is suffering from food shortages, owing to poor public policies.
- There is a trade-off between high investment/high efficiency agricultural systems and small holder agriculture in many countries in the Americas. This social trade-off is a major public policy issue.
- Trade in agricultural products has historically been distorted by subsidies and barriers to market access. These distortions will need to be reduced in the future.
- Most countries in the Americas need better functioning policies and more effective enforcement to promote the sustainability of forest, marine, inland and groundwaters, and all other terrestrial ecosystems and their biodiversity.
- Poverty eradication and FNS are closely linked goals that must be pursued together.
- The secondary effects of agricultural policies should be considered, such as migration of the rural population to urban centres, and impacts on land use and conservation.
- In many countries, regulations relating to such things as pesticide use, over-use of antibiotics, organic agriculture and the reduction of food waste are inadequate.
- Evidence-based regulation should be improved to more effectively combat food-borne diseases.
- There is an important role for international aid donors and non-governmental organisations in advancing STI-based FNS in many countries in the Americas.
- The potential for involving the Organization of American States more actively in facilitating STI-based approaches to FNS must be explored.
- Organisations such as IANAS can also accelerate progress by reaching out to national policy-makers and advocating for evidence-based FNS policies. IANAS has a significant presence in most countries in the Americas through the national science academies.

11. **The gradual shift in STI investment from public to private sectors must be monitored and understood, so that gaps in public support can be prioritised.**

- The low research participation of the private sector in most counties is deemed a major deficit.
- There is a need for better methods for communicating STI advances and investment opportunities to national policy-makers and the public.

The challenge for the Americas will be to retain the ability to feed and adequately nourish itself while also making a substantial contribution to the food supplies available to the rest of the world.

EASAC

EASAC (2017). Opportunities and challenges for research on food and nutrition security and agriculture in Europe. On https://easac.eu/projects/details/food-and-nutrition-security-and-agriculture/

We frame our specific EASAC recommendations within the context of strategic dimensions that determine a wide range of actions in science and policy:

- The interfaces between research on the nutrition-sensitivity of food and agriculture systems and on environmental sustainability must be addressed to connect scientific knowledge on natural resources to the food value chain. The sustainable bioeconomy and circular economy provide for new overarching frameworks, going beyond traditional concepts of economic sectors.

- The focus cannot be only on populations in general but should also cover particular issues for vulnerable groups such as mothers and children, the elderly, patients and migrants. This requires systematic, longitudinal data collection to generate robust resources, together with cross-disciplinary research, encompassing economics and social sciences as well as the natural sciences, to understand vulnerable groups and the more general aspects of consumer behaviour.

- Large data sets, based on comparable and verifiable methodology, are a vital tool to support innovation throughout the food system and to prepare for risk and uncertainty. There is much to be done to fill data gaps, to agree improved procedures for data collection, curation, analysis and sharing, while also addressing data ownership and privacy concerns.

- To contribute with evidence to options for reform of the present Common Agricultural Policy towards devising an EU food and nutrition policy that rewards innovation, reduces risks, focusses on public goods, takes account of the varying national interests and cultures and contributes to benefitting the rest of the world.

- EU development assistance should be viewed broadly, to include international collaborative research; research in the EU on priorities for global food systems, their resilience and perturbations; sharing of science and technology especially related to FNS; and resolution of international governance issues of food and agriculture.

- Ensuring that regulatory and management frameworks are evidence-based, proportionate and sufficiently flexible to prepare for and enable advances in science.

Within this overall framework for European strategy development, our report identifies many opportunities to generate, connect and use research. Among specific scientific opportunities are the following:

1. Nutrition, food choices and food safety

- Understanding the drivers of dietary choices, consumer demand and how to inform and change behaviour, including acceptance of innovative foods and innovative diets.

- Tackling the perverse price incentives to consume high calorie diets and introducing new incentives for healthy nutrition.

- Clarifying what is a sustainable, healthy diet and how to measure sustainability related to consumption.

- Exploring individual responsiveness to nutrition and the links to health.

- Promoting research interfaces between nutrition, food science and technology, the public sector and industry.

- Evaluating how to make food systems more nutrition-sensitive.

- Characterising sources of food contamination and the opportunities for reducing food safety concerns that may arise from implementation of other policy objectives (for example, the circular economy goal of recycling of waste materials).

- Compiling analytical tests to authenticate food origin and quality.

- Assessing any disconnects between the implications of the COP 21 objectives for livestock and meat consumption, and standard recommendations for consuming healthy diets.

2. Plants and animals in agriculture

- For livestock, determining how to capitalise on genomics research for food production and for animal health and welfare. This includes the rapidly advancing science of genome editing and the increasing significance of characterising genetic material conserved in gene banks.

- For the oceans, improving the knowledge base for sustainable harvest and culturing of lower trophic level marine resources and exploring the potential for biomass provision to diminish pressures on agricultural land, freshwater and fertilisers.

- For crops, progressing understanding of the genetics and metabolomics of plant product quality. This also includes capitalising on the new opportunities coming within range for the targeted modification of crops using genome editing.
- For plants as for animal science, it is important to protect wild gene pools and to continue sequencing of genetic resources to unveil the potential of genetic resources.

3. Environmental sustainability

- Evaluating climate resilience throughout food systems and transforming food systems to mitigate their global warming impact.
- Capitalising on opportunities to co-design research across disciplines to understand better the nexus food-water-other ecosystem services and to inform the better coordination of relevant policy instruments, including the Common Agricultural Policy, Water Framework Directive and the Habitats Directive. Efforts to increase the efficiency of food systems should not focus on increasing agricultural productivity by ignoring environmental costs.
- Developing an evidence base to underpin land and water use in providing the range of private and public goods required in a sustainable way, appropriate to place.
- Regarding biofuel choices, the immediate research objectives for the next generation of biofuels include examining the potential of cellulosic raw materials.
- Research should continue to explore the value of synthetic biology and other approaches to engineer systems with improved photosynthesis. There is also continuing need for research to clarify impacts of biomass production on land use and food prices.
- For soil, expanding research to understand and quantify the potential value of soil in carbon sequestration and, hence, climate change mitigation. There is a broad research agenda to characterise other functions of soil and the soil microbiome and contribute to the bioeconomy, for example as a source of novel antibiotics. Research is also important to support cost-effective soil monitoring and management, particularly to underpin the reduced use of fertilisers and improve biodiversity.

4. Waste

- Committing to the collection of more robust data on the extent of waste in food systems and the effectiveness of interventions to reduce waste at local and regional levels.
- Ensuring the application of food science and technology and agronomy in novel approaches to processing food and reducing waste, and in informing the intersection between circular economy and bioeconomy policy objectives.

5. Trade and markets

- Increasing commitment to data collection on trade flows and prices with modelling and analysis of databases.
- Examining linkages between extreme events and price volatility, evaluating the effects of regulatory policy instruments in agricultural commodity markets and the price transmission between global commodity markets and local food systems.
- Ascertaining the science agenda for understanding the characteristics of fair trade systems, for example the non-tariff conditions associated with variation in regulatory policy, labelling or other food safety requirements.

6. Innovation trends

- In each of the above-mentioned specific areas of science opportunities the linkages between basic science and problem-solving applied science seem likely to become more closely related in the future. This is so in the fields of biosciences, digitisation, mathematics and farm precision technologies, health and behaviour, as well as in complex environmental and food system modelling. This has consequences for the redesign of the science landscape and for science teaching and the training of next-generation scientists to address food, nutrition and agriculture issues.

- We emphasise the key role of agricultural sciences for European competitiveness and urge a rebalancing of commitments – to shift budget items from agricultural subsidies towards innovation in the pending reform of the Common Agricultural Policy.

Abbreviations

ASEAN	Association of Southeast Asian Nations
AASSA	Association of Academies and Societies of Sciences in Asia
AU	African Union
CFS HLPE	Committee on World Food Security High Level Panel of Experts on Food Security and Nutrition
CGIAR	Consultative Group on International Agricultural Research
COP	Conference of the Parties of the UN Framework Convention on Climate Change
CRISPR–Cas9	Clustered regularly interspaced short palindromic repeats–CRISPR-associated protein-9 nuclease
EASAC	European Academies' Science Advisory Council
EU	European Union
FAO	Food and Agriculture Organization
FNS	Food and nutrition security
FNSA	Food and nutrition security and agriculture
GBD	Global burden of diseases
GDP	Gross domestic product
GHG	Greenhouse Gases
GMO	Genetically modified organism
GPS	Global positioning system
IANAS	InterAmerican Network of Academies of Sciences
IAP	InterAcademy Partnership
ICSU	International Council for Science
ICT	Information and communication technology
IFPRI	International Food Policy Research Institute
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
IRP	International Resource Panel of the UN Environment Programme
NASAC	Network of African Science Academies
NBT	New plant breeding technique
NCD	Non-Communicable Disease
OECD	Organisation for Economic Co-operation and Development
R&D	Research and development
SDG	Sustainable Development Goal
STI	Science, technology and innovation
TFP	Total factor productivity
TRP	Total resource productivity
UN	United Nations
UNEP	United Nations Environment Programme
UNICEF	United Nations Children's Fund
WFP	United Nations World Food Programme
WHO	World Health Organization
WTO	World Trade Organization

References

Adams J and White M (2015). Characterisation of UK diets according to degree of food processing and association with socio-demographics and obesity: cross-sectional analysis of UK National Diet and Nutrition survey (2008-2012). *International Journal of Behavioral Nutrition and Physical Activity* **12**, 160.

Adenle AA *et al*. (2018). Rationalizing governance of genetically modified products in developing countries. *Nature Biotechnology* **36**, 137–139.

Aleksandrowicz L, Green R, Joy E JM, Smith P and Haines A (2016). The impacts of dietary change on greenhouse gas emissions, land use, water use, and health. A systematic review. *PLoS ONE* **11**, e0165797.

Alexander DD and Cushing CA (2011). Red meat and colorectal cancer: a critical summary of prospective epidemiological studies. *Obesity Reviews* **12**, e472–e473.

Alexander P and Moran D (2017). Rethinking food waste for a healthier planet. *Lancet Planetary Health* **1**, e170–e171.

d'Amour CB, Wenz L, Kalkuhl M, Steckel JC and Creutzig F (2016). Teleconnected food supply shocks. *Environmental Research Letters* **11**, 035007.

Annan K (2018). Data can help to end malnutrition across Africa. *Nature* **555**, 7.

Anon. (2017a). Expanding research views. *Nature Climate Change* **7**, 229.

Anon. (2017b). Addressing the vulnerability of the global food system. *Lancet* **390**, 95.

Anon. (2018). Chinese project offers a brighter farming future. *Nature* **555**, 141.

Asaduzzaman M (2018). Antimicrobial resistance: an urgent need for a planetary and ecosystems approach. *Lancet Planetary Health* **2**, e99–e100.

Bassi R, Morelli G and Salamini F (2017). Xylella. *Accademia Nazionale dei Lincei.* On http://www.lincei.it/files/documenti/Report_Xylella_verEN2.pdf

Baugreet S, Hamill RM, Kerry JP and McCarthy SN (2017). Mitigating nutrition and health deficiencies in older adults: a role for food innovation? *Journal of Food Science* **82**, 848–855.

Beachy RN (2014). Building political and financial support for science and technology for agriculture. *Philosophical Transactions of the Royal Society B* **369**, 20120274

Bero L (2017). Developing reliable dietary guidelines. *British Medical Journal* **359**, j4845.

Blanchard JL *et al*. (2017). Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nature Ecology and Evolution* **1**, 1240.

Blecher E *et al.* (2017). Global trends in the affordability of sugar-sweetened beverages 1990-2016. *Preventing Chronic Disease* **14**, 160406.

Bloem S and de Pee S (2017). Developing approaches to achieve adequate nutrition among urban populations requires an understanding of urban development. *Global Food Security* **12**, 80–88.

Bosch R, van de Pol M and Philp J (2015). Policy: define biomass sustainability. *Nature* **523**, 526–527.

Briggs ADM (2016). Sugar tax could sweeten a market failure. *Nature* **531**, 551.

Bullock JM *et al*. (2017). Resilience and food security: rethinking an ecological concept. *Journal of Ecology* **105**, 880–884.

Burke M and Lobell D (2017). Satellite-based assessment of yield variation and its determinants in smallholder African systems. *Proceedings of the National Academy of Sciences of the USA* **114**, 2189–2194.

Byndloss MX and Baumier AJ (2018). The germ-organ theory of non-communicable diseases. *Nature Reviews Microbiology* **16**, 103–110.

Carlson KM *et al.* (2017). Greenhouse gas emissions intensity of global croplands. *Nature Climate Change* **7**, 63–68.

CFS High Level Panel of Experts on Food Security and Nutrition (2017). Nutrition and food systems. On http://www.fao.org/3/a-i7846e.pdf.

CGIAR (2015). CGIAR Strategy and Results Framework 2016–2030: Overview. On https://cgspace.cgiar.org/handle/10947/4069

Challinor AJ, Adger WN and Benton TG (2017). Climate risks across borders and scales. *Nature Climate Change* **7**, 621–623.

Cimino AM, Boyles AL, Thayer KA and Perry MJ (2017). Effects of neonicotinoid pesticide exposure on human health: a systematic review. *Environmental health perspectives*, **125**, 155.

Cosstick N (2017). Monitoring the global food system: building trust and resilience for UK citizens and consumers. *University of Cambridge Centre for Science and Policy*.

Dalin C, Wada Y, Kastner T and Puma MJ (2017). Groundwater depletion embedded in international food trade. *Nature* **543**, 700–704.

Dance A (2017). Engineering the animal out of animal products. *Nature Biotechnology* **35**, 704–707.

Dangour A D, Mace G and Shankar B (2017). Food systems, nutrition, health and the environment. *The Lancet Planetary Health* **1**, e8–e9.

Dehghan M *et al.* (2017). Association of fats and carbohydrate intake with cardiovascular disease and mortality in 18 countries from five continents (PURE): a prospective cohort study. *Lancet* **390**, 2050–2062.

Dinesh D, Campbell BM, Bonilla-Findji O and Richards M (editors) (2017). 10 best bet innovations for adaptation in agriculture: A supplement to the UNFCCC NAP Technical Guidelines. On https://cgspace.cgiar.org/bitstream/handle/10568/89192/CCAFSWP215.pdf

Downs S, Payne A and Swartz H (2017). Enhancing sustainable diets with data collection and policy analysis. The Economist Intelligence Unit. On http://foodsustainability.eiu.com/enhancing-sustainable-diets-data-collection-policy-analysis/.

Drewnowski A (2017). Measures and metrics of sustainable diets with a focus on milk, yogurt, and dairy products. *Nutrition Reviews* **76**, 21–28.

El-Chichakli B, von Braun J, Lang C, Barben D and Philp J (2016). Five cornerstones of a global bioeconomy. *Nature* **535**, 221–223.

Etemadi A, Sinha R, Ward MH, Graubard BI, Inoue-Choi M, Dawsey SM and Abnet CC (2017). Mortality from different causes associated with meat, heme iron, nitrates and nitrites in the NIH-AARP Diet and Health Study. *British Medical Journal* **357**, j1957.

EU-Africa High Level Policy Dialogue on Science, Technology and Innovation (2016). Roadmap towards a jointly funded EU-Africa research and innovation partnership on food and nutrition security and sustainable agriculture. *DG Research and Innovation, European Commission.* On https://ec.europa.eu/research/iscp/pdf/policy/eu-africa_roadmap_2016.pdf

European Environment Agency (2017). Climate change, impacts and vulnerability in Europe 2016. An indicator-based report. EEA Report Ni 1/2017.

European Parliamentary Research Service (2017). Urban agriculture in Europe. PE 614.641. On http://www.europarl.europa.eu/RegData/etudes/IDAN/2017/614641/EPRS_IDA(2017)614641_EN.pdf

Fanzo J, McLaren R, Davis C and Choufani J (2017). How to ensure nutrition for everyone under climate change and variability. *GCAN Policy note 1, Feed the Future.* On http://www.ifpri.org/publication/how-ensure-nutrition-everyone-under-climate-change-and-variability.

FAO (2015). The Intergovernmental Technical Panel on Soils (ITPS). Status of the World's Soil Resources. On http://www.fao.org/documents/card/en/c/c6814873-efc3-41db-b7d3-2081a10ede50/.

FAO (2016). Crop prospects and food situation. Report No. 4. On http://www.fao.org/documents/card/en/c/bdb67528-37d2-41d9-9e6a-4398f196b7ec/

FAO (2017). The future of food and agriculture: trends and challenges. Report as preparation for FAO Medium-term Plan 2018-2021. On http://www.fao.org/3/a-i6583e.pdf.

FAO (2017). Critical and emerging Issues in Food Security and nutrition. On http://www.fao.org/cfs/cfs-hlpe/critical-and-emerging-issues/en/.

FAO, IFAD, UNICEF, WFP and WHO (2017). The state of food security and nutrition in the world. On http://www.fao.org/3/a-i7695e.pdf.

Food Security Information Network (2017). Global report on food crises 2017. On https://ec.europa.eu/europeaid/sites/devco/files/wfp291270.pdf.

Foottit RG and Adler PH (2009). Insect biodiversity: science and society. Blackwell.

Frelat R *et al.* (2016). Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proceedings of the National Academy of Sciences of the USA* **113**, 458–463.

Garb Y and Friedlander L (2014). From transfer to translation: using systemic understandings of technology to understand drip irrigation uptake. *Agricultural Systems* **128**, 13–24.

GBD 2016 SDG Collaboration (2017). Measuring progress and projecting attainment on the basis of past trends of the health-related Sustainable Development Goals in 188 countries: an analysis from the Global Burden of Disease Study 2016. *Lancet* **390**, 1423–1459.

Gernand AG, Schulze KJ, Stewart CP, West Jr KP and Christian P (2016). Micronutrient deficiencies in pregnancy worldwide: health effects and prevention. *Nature Reviews Endocrinology* **12**, 274–289.

Ghaffarzadeh K (2017). Deep learning for agchems. *Chemistry and Industry* **09**, 36

Guohui M, Yuan LP, Peisong H and Yeyun X (2014). In: Hybrid Rice Achievements, Development and Prospect in China. Expert Consultation on Hybrid Rice Development in Asia: Assessment of Limitations and Potential, Bangkok, Thailand.

Golden CD, Allison EH, Cheung WW, Dey MM, Halpern BS, McCauley DJ, Smith M, Vaitla B, Zeller D. and Myers SS (2016). Fall in fish catch threatens human health. *Nature* **534**, 317–320.

Green JM, Barratt MJ, Kinch M and Gordon JI (2017). Food and microbiota in the FDA regulatory framework. *Science* **357**, 39–40.

Haddad L (2015). The research implications of the global nutrition report. On www.scidev.net/global/nutrition/opinion/implications-of-nutrition-report.html.

Haddad L *et al.* (2016). A new global research agenda for food. *Nature* **540**, 30–32.

Halle MG, Wossen T, Tesfaye K and von Braun J (2017). Impact of climate change, weather extremes, and price risk on global food supply. *Economics of Disasters and Climate Change* **1**, 55–75.

Herrero M, Thornton PK, Power B, Bogard JR, Remans R, Fritz S, Gerber JS, Nelson G, See L, Waha K and Watson RA (2017). Farming and the geography of nutrient production for human use: a transdisciplinary analysis. *Lancet Planetary Health* **1**, e33–e42.

Hidrobo M, Hodinott J, Kumar N and Oliver M (2018). Social protection, food security and asset formation. *World Development* **101**, 88–103.

Holmes A, Holmes M, Gottlieb T, Price LB and Sundsfjord A (2018). End non-essential use of antimicrobials in livestock. *British Medical Journal* **360**, k259.

Horton P *et al.* (2017). An agenda for integrated system-wide interdisciplinary agri-food research. *Food Security* **9**, 195–210.

Hyseni L *et al*. (2017). The effects of policy actions to improve population dietary patterns and prevent diet-related non-communicable diseases: scoping review. *European Journal of Clinical Nutrition* **7**, 694–711.

IAP (2018). Assessing the security implications of genome editing technology. On http://www.interacademies.org/45511/Assessing-Security-Implications-of-Genome-Editing-Emerging-Points-From-an-International-Workshop.

ICSU (2017). A guide to SDG interactions: from science to implementation. On www.icsu.org/cms/2017/05/SDGs-interactions-executive-summary.pdf

IFPRI (2016). 2016 Global nutrition report. On https:/www.ifpri.org/publication/global-nutrition-report-2016-promise-impact-ending-malnutrition-2030.

IFPRI (2017a). Global food policy report. On http://www.ifpri.org/publication/2017-global-food-policy-report.

IFPRI (2017b). Agriculture, development, and the global trading system: 2000-2015. On http://www.ifpri.org/publication/agriculture-development-and-global-trading-system-2000%E2%80%93-2015.

IRP (2017). Assessing global resource use: a systems approach to resource efficiency and pollution reduction. Report of the International Resource Panel, United Nations Environment Programme. On http://www.resourcepanel.org/sites/default/files/documents/document/media/assessing_global_resource_use_amended_130318.pdf

Jean N, Burke M, Xie M, Davis M, Lobell D and Ermon S (2016). Combining satellite imagery and machine learning to predict poverty. *Science* **353**, 790–794.

Jones AD and Ejeta G (2016). A new global agenda for nutrition and health: the importance of agriculture and food systems. *Bulletin of the World Health Organization* **94**, 228–229.

Kalkuhl M, von Braun J and Torero M (2016). Food price volatility and its implications for food security and policy. Springer Open Access. On https://link.springer.com/book/10.1007/978-3-319-28201-5

Kanter R, Walls HL, Tak M, Roberts F and Waage J (2015). A conceptual framework for understanding the impacts of agriculture and food systems policies on nutrition and health. *Food Security* **7**, 767–777.

Khoury CK *et al.* (2014). Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences of the USA* **111**, 4001–4006.

King A (2017). The future of agriculture. *Nature* **544**, S21–S23.

Kittinger JN *et al.* (2017). Committing to socially responsible seafood. *Science* **356**, 912–913.

Kongerslev Thorning T, Bertram HC, Bonjour J-P, de Groot L, Dupont D, Feeney E, Ipsen R, Lecerf JM, Mackie A, McKinley MC, Michalski M-C, Rémond D, Risérus U, Soedamah-Muthu SS, Tholstrup T, Weaver C, Astrup A and Givens I (2017). Whole dairy matrix or single nutrients in assessment of health effects: current evidence and knowledge gaps. *American Journal of Clinical Nutrition* **105**, 1033–1045.

Li T *et al.* (2018). Swift acid rain sensing by synergistic rhizospheric bioelectrochemical responses. *ACS Sensors*. On https://doi.org//10.1021/acssensors.8b00401.

Liang X-Z *et al.* (2017). Variance in crop yields. *Proceedings of the National Academy of Sciences of the USA* **114**, E2285–E2292.

Lin J, Zhang SM, Cook NR, Lee IM and Buring JE (2004). Dietary fat and fatty acids and risk of colorectal cancer in women. *American Journal of Epidemiology* **160**, 1011–1022.

Liu Y and Li Y (2017). Revitalize the world's countryside. *Nature* **548**, 275–277.

Lowenberg-DeBoer J and Musa S (2017). University licensing of intellectual property In developing countries: a case study of the Purdue improved crop storage (Pics) technology. Working paper 17-2. On https://ageconsearch.umn.edu/bitstream/254126/2/17-2.University%20Licensing%20of%20IP.PICS.pdf

Macdiarmid JI, Douglas F and Campbell J (2016). Eating like there's no tomorrow. Public awareness of the environmental impact of food and reluctance to eat less meat as part of a sustainable diet. *Appetite* **96**, 487–493.

Macleod A, Jones GD, Anderson HM and Mumford RA (2016). Plant health and food security, linking science, economics, policy and industry. *Food Security* **8**, 17–25.

Maffioli SI *et al.* (2017). Antibacterial nucleoside-analog inhibitor of bacterial RNA polymerase. *Cell* **169**, 1240–1248.

Malabo Montpellier Panel (2017). Nourished: how Africa can build a future free from hunger and malnutrition. On https://www.mamopanel.org/resources/reports-and-briefings/nourished-how-africa-can-build-future-free-hunger-/.

Mayer EA, Tillisch K and Gupta A (2015). Gut/brain axis and the microbiota. *Journal of Clinical Investigation* **125**, 926–938.

Medek DE, Schwartz J and Myers SS (2017). Estimated effects of future atmospheric CO_2 concentrations on protein intake and the risk of protein deficiency by country and region. *Environmental Health Perspectives* **125**, 087002.

Mottet A, de Haan C, Falcucci A, Tempio G, Opio C and Gerber P (2017). Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security* **14**, 1–8.

Muller A and Schader C (2017). Efficiency, sufficiency, and consistency for sustainable healthy food. *Lancet Planetary Health* **1**, e13–e14.

Myers SS, Smith MR, Guth S, Golden CD, Vaitla B, Mueller ND, Dangour AD and Huybers P (2017). Climate change and global food systems: potential impacts on food security and undernutrition. *Annual Review of Public Health* **38**, 259–277.

Myers SS, Wessells KR, Kloog J, Zanobetti A and Schwartz J (2015). Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study. *Lancet Global Health* **3**, e639–e645.

Myers SS, Zanobetti A, Kloog I, Huybers P, Leakey AD, Bloom AJ, Carlisle E, Dietterich LH, Fitzgerald G, Hasegawa T and Holbrook NM (2014). Increasing CO_2 threatens human nutrition. *Nature* **510**, 139–142.

National Academies of Sciences, Engineering, Medicine (2018). Science breakthroughs to advance food and agricultural research by 2030. Consensus Study Report. On https://www.nap.edu/catalog/25059/

Nelson A (2017). Crop pests: crop-health survey to fill data gaps. *Nature* **541**, 464.

Nelson R, Wiesner-Hanks T and Balint-Kurti P (2018). Navigating complexity to breed disease-resistant crops. *Nature Reviews Genetics* **19**, 21–33.

Newbold T *et al.* (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? *Science* **353**, 288–291.

NCD Risk Factor Collaboration (2016). Trends in adult body-mass index in 200 countries from 1975 to 2014: a pooled analysis of 1698 population-based measurement studies with 19.2 million participants. *Lancet* **387**, 1377–1396.

OECD (2016). Alternative futures for global food and agriculture. DOI: http://dx.doi.org/10.1787/9789264247826-2-en.

Office of Agricultural Economics of Thailand (2015). Agricultural Statistics of Thailand 2015, 2-32.

Omilola B and Robele S (2017). Discussion paper: The central position of agriculture within the 2030 Agenda for Sustainable Development. IFPRI, on http://ebrary.ifpri.org/cdm/singleitem/collection/p15738coll2/id/131489.

Pardey PG, Chang-Kang C, Dehmer SP and Beddow JM (2016). Agricultural R&D is on the move. *Nature* **537**, 301–03.

Pardey PG *et al*. (2018). The shifting structure of agricultural R&D: worldwide investment patterns and payoffs. In *From Agriscience to Agribusiness*, Springer p13–39.

Pontifical Academy of Sciences (2017). Declaration of the health of people, health of planet and our responsibility. Climate change. Pollution and health workshop.

Poore J and Nemecek T (2018). Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992.

Porter JR, Howden M and Smith P (2017). Considering agriculture in IPCC assessments. *Nature Climate Change* **7**, 680–683.

Pretty J *et al.* (2010). The top 100 questions of importance to the future of global agriculture. *International Journal of Agricultural Sustainability* **8**, 219–236.

Qin J, Li R, Raes J, Arumugam M, Burgdorf KS, Manichanh C, Nielsen T, Pons N, Levenez F, Yamada T and Mende DR (2010). A human gut microbial gene catalogue established by metagenomic sequencing. *Nature*, **464**, 59–65.

Reddy KS (2016). Global Burden of Disease Study 2015 provides GPS for global health 2030. *Lancet* **388**, 1448–1449.

Reynolds MP *et al.* (2017). Improving global integration of crop research. *Science* **357**, 359–360.

Rippke U *et al.* (2016). Timescales of transformational climate change adaptation into sub-Saharan Africa. *Nature Climate Change* **6**, 605–609.

Romani S, Grappi S, Bagozzi RP and Barone AM (2018). Domestic food practices: a study of food management behaviors and the role of food preparation planning in reducing waste. *Appetite* **121**, 215–227.

Rutherfurd SM, Bains K and Moughan PJ (2012). Available lysine and digestible amino acid contents of proteinaceous foods of India. *British Journal of Nutrition* **108**, S59–S68.

Sachs JD and Schmidt-Traub G (2017). Global lessons for sustainable development goals. *Science* **356**, 32–33.

Sahakian M (2015). Getting emotional: historic and current changes in food consumption practices viewed through the lens of cultural theories. In Putting Sustainability into Practice: Advances and

Applications of Social Practice Theories (Kennedy EH, Cohen MJ and Krogman N, editors). Edward Elgar.

Sattari SZ, Bouwman AF, Martinez Rodriguiz R, Beusen AHW and van Ittersum MK (2016). Negative global phosphorus budgets challenge sustainable intensification of grasslands. *Nature Communications* **7**, doi: 10.1038/ncomms10696.

Scientific Advisory Board of the UN Secretary-General (2016). Food security and health policy. On http://unesdoc.unesco.org/images/0024/002468/246887E.pdf.

Sen A (1981). Poverty and famines: an essay on entitlement and deprivation. Oxford University Press.

Seto KC and Ramankutty N (2016). Hidden linkages between urbanization and food systems. *Science* **352**, 943–945.

Sharma KK *et al.* (2018). Peanuts that keep aflatoxin at bay: a threshold that matters. *Plant Biotechnology Journal* **16**, 1024–1033.

Shepherd GS and Gelderblom WC (2014). Rapid testing and regulating for mycotoxin concerns: a perspective from developing countries. *World Mycotoxin Journal* **7**, 431–437.

Singh N and Singh P (2011). Amaranth: potential source for flour enrichment. In Preely V, Watson R and Patel V (editors) *Flour and Bread and their Fortification in Health and Disease Prevention*. Elsevier p101–111.

Snyder KA, Miththapala S, Sommer R and Braslow J (2017). The yield gap: closing the gap by widening the approach. *Experimental Agriculture* **53**, 445–459.

Spielman DJ, Kolady DE and Ward PS (2013). The prospects for hybrid rice in India. *Food security* **5**, 651–665.

Springmann M *et al.* (2016). Global and regional health effects future food production under climate change: a modelling study. *Lancet* **387**, 1937–1946.

Springmann M *et al.* (2017). Mitigation potential and global health impacts from emissions pricing of food commodities. *Nature Climate Change* **7**, 69–74.

Swaminathan MS and Kesavan PC (2015). Energy provision and food security in off-grid villages. In: *Smart Villages – new thinking for off -grid communities worldwide*, Heap RB (editor) 56–62.

Taylor J and Ayango JO (2011). Sorghum flour and flour products: production, nutritional quality and fortification. In Preely V, Watson R and Pavel V (editors) *Flour and Breads and their Fortification in Health and Disease Prevention*. Elsevier p127–139

Teng P, Caballero-Anthony M, Lassa J and Nair T (2015). Towards Asia 2025 in policy and technology imperatives. Summary of the main findings of the second international conference on Asian food security held in Singapore on 21–22 August 2014. *Food Security* **7**, 159–165.

Thilsted SH *et al.* (2016). Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy* **61**, 126–131.

Thornton PK and Herrero M (2015). Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nature Climate Change* **5**, 830–836.

Vanlauwe B, Six J, Sanginga N and Adesina AA (2015). Soil fertility decline at the base of rural poverty in sub-Saharan Africa. *Nature Plants* **1**, 15101.

Vauzour D *et al*. (2017). Nutrition for the ageing brain: towards evidence for an optimal diet. *Ageing Research Reviews* **35**, 222–240.

Venugopal PD and Dively GP (2017). Climate change, transgenic corn adoption and field-evolved resistance in corn earworm. *Royal Society Open Science* **4**, 170210

Vetter S *et al.* (2017). Greenhouse gas emissions from agricultural food production to supply Indian diets: implications for climate change mitigation. *Agriculture, Ecosystems and Environment* **237**, 234–241.

Viciani E (2017). Carpe diet. *Nature Reviews Microbiology* **15**, 644.

von Braun J and Birner R (2017). Designing global governance for agricultural development and food and nutrition security. *Review of Development Economics* **21**, 265–284.

von Braun J, Gulati A and Kharas H (2017). Key policy actions for sustainable land use and water use to serve people. *Economics: The Open-Access, Open-Assessment Journal* **11**, 1–14.

von Braun J (2017). Agricultural change and health and nutrition in emerging economies. In: *Agriculture and Rural Development in a Globalizing World* (ed. Pingali P and Feder G), chapter 14, pp. 273–291. London: Routledge.

von Braun J, Teklu T and Webb P (1998). Famine in Africa: causes, responses and prevention. The Johns Hopkins University Press.

Watts N *et al.* (2017). The *Lancet* Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *Lancet* **391**, 581–630. On http://dx.doi.org/10.1016/S0140-6736(17)32464-9.

Wellesley L, Happer C and Froggatt A (2015). Changing climate, changing diets: pathways to lower meat consumption. Royal Institute of International Affairs, Chatham House.

Wesseler J, Smart RD, Thomson J and Zilberman D (2017). Foregone benefits of important food crop improvements in sub-Saharan Africa. *PLoS ONE* **12**, e0181353.

Wesseler J and von Braun J (2017). Measuring the bioeconomy: economics and policies. *Annual Review of Resource Economics* **9**, 275–298.

Whitfield S, Challinor AJ and Rees RM (2018). Frontiers in climate smart food systems: outlining the research space. *Frontiers in Sustainable Food Systems* **2**, 2.

WHO (2017). Ambition and action in nutrition 2016–2025. On http://www.who.int/nutrition/publications/nutrition-strategy-2016to2025/en/

Wood SA, Smith MR, Fanzo J, Remans R and DeFries RS (2018a). Trade and the equitability of global food nutrient distribution. *Nature Sustainability* **1**, 34–37.

Wood SLR *et al*. (2018b). Distilling the role of ecosystem services in the Sustainable Development Goals. *Ecosystem Services* **29**, 70–82.

World Bank (2016). The future of food: shaping the global food system to deliver improved nutrition and health. On https://openknowledge.worldbank.org/handle/10986/24104.

World Bank (2017a). Future of food: shaping the food system to deliver jobs. On http://www.worldbank.org/en/topic/agriculture/publication/the-future-of-food-shaping-the-food-system-to-deliver-jobs.

World Bank (2017b). Agriculture and food. On http://www.worldbank.org/en/topic/agriculture.

Wunsche J, Lambert C, Gole U and Biesalski HK (2018). Consumption of gluten free products increases heavy metal intake. *NFS Journal* **12**, 11–15.

Zampieri M, Ceglar A, Dentener F and Toreti A (2017). Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environmental Research Letters* **12**, p 064008.

Zimmerer KS and S de Haan (2017). Agrobiodiversity and a sustainable food future. *Nature Plants* **3**, 17047.

The InterAcademy Partnership (IAP) was formally launched in South Africa in March 2016, bringing together three established networks of academies of science, medicine and engineering, now re-named as IAP for Science, IAP for Research and IAP for Health.

Under the new InterAcademy Partnership, more than 130 national and regional member academies work together to support the special role of science and its efforts to seek solutions to address the world's most challenging problems. In particular, IAP harnesses the expertise of the world's scientific, medical and engineering leaders to advance sound policies, improve public health, promote excellence in science education, and achieve other critical development goals.

InterAcademy Partnership
ICTP Campus, c/o TWAS
Strada Costiera 11
34151 Trieste
Italy

InterAcademy Partnership
US National Academies of Science, Engineering, and Medicine
500 Fifth St. NW
Washington, DC 20001
USA

www.interacademies.org
iap@twas.org
secretariat@iapartnership.org

SPONSORED BY THE

Federal Ministry of Education and Research

SUSTAINABLE DEVELOPMENT GOALS