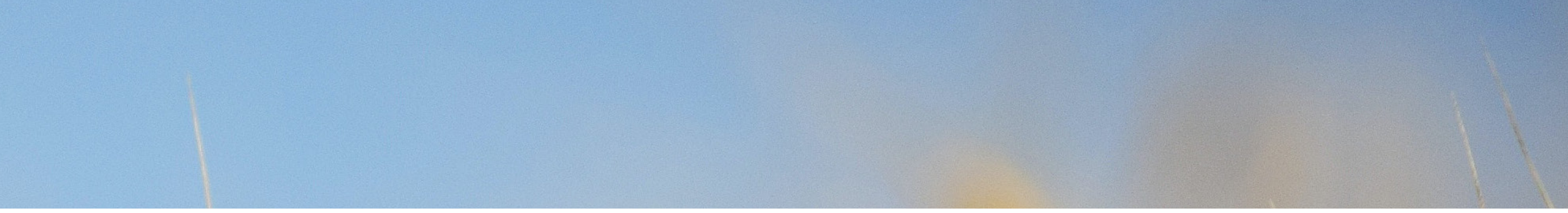

IAP
Food Systems Summit Briefs

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About the InterAcademy Partnership (IAP)

Under the umbrella of the InterAcademy Partnership (IAP), more than 140 national, regional and global member academies work together to support the vital role of science in seeking evidence-based solutions to 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.

IAP's four regional networks in Africa (the Network of African Science Academies, NASAC), the Americas (the InterAmerican Network of Academies of Sciences, IANAS), Asia (the Association of Academies and Societies of Sciences in Asia, AASSA) and Europe (the European Academies' Science Advisory Council, EASAC) are responsible for managing and implementing many IAP-funded projects and help make IAP's work relevant around the world. For more information about IAP see https://www.interacademies. org and follow IAP on Twitter https://twitter.com/IAPartnership, LinkedIn https://www. linkedin.com/company/interacademypartnership and YouTube https://tinyurl.com/ IAPyoutube.

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Foreword

The UN Food Systems Summit (UN FSS) provides a very important collective initiative to identify and assess the scientific opportunities for transforming food systems. Although much progress had been made in past decades, the global prospects for food and nutrition security are now worsening and are being exacerbated by the concurrent crises of the COVID-19 pandemic and climate change.

Nonetheless, it is also now possible to capitalise on unprecedented scientific advances. The InterAcademy Partnership (IAP), the global network of more than 140 academies of science, engineering and medicine, published a report in 2018 on the opportunities and challenges for food and nutrition security and agriculture. Our global synthesis report was informed by four regional reports by academy networks in Africa (NASAC), Asia-Pacific (AASSA), the Americas (IANAS) and Europe (EASAC). These reports highlighted the importance of taking a transdisciplinary approach to food systems and encompassing multiple steps from growing through to transport, retail, consumption and recycling. Furthermore, all agreed that in the transformation of food systems towards social, economic and environmental sustainability, it was also essential and urgent to take account of pressures on other natural resources such as soil and water, and the of continuing objective to avoid further damage to biodiversity.

Earlier in 2021, IAP greatly welcomed an invitation from the UN FSS Scientific Group to contribute regional and global Briefs, updating material selected from our previous reports. These were published by the UN FSS two months ago. We now bring these Briefs together in a single volume as a resource to help stimulate further discussion and action, in the run-up to the Summit and afterwards. Taking account of regional similarities and differences, we evaluate a wide range of scientific opportunities that can contribute strongly to tangible progress in transforming food systems; that can be mapped on to the UN FSS Action Tracks; and that can inform the identification and introduction of game changers. Taken together, the many recent scientific advances and further achievements now coming within reach, constitute a core resource to stimulate innovation, guide practice and inform policy decisions. We thank the authors of the Briefs, and the experts they consulted, for their continuing commitment to these timely and important topics and for ensuring that the distinctive approach of IAP adds value to the work of many other groups in this area. We also thank our regional academy networks, AASSA, EASAC, IANAS and NASAC, and our IAP colleagues for their enthusiastic and sustained support for this major IAP project.

The issues raised by the UN FSS, which are vitally important to us all, require considerable further effort in transdisciplinary, cross-sectoral and cross-boundary partnerships. We affirm that IAP and its members are keen to continue our work at the science-policy interfaces and to use our experience and motivation at national, regional and global levels to engage with all stakeholders. We greatly welcome feedback on any of the issues discussed in this volume.

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The role of science, technology, and innovation for transforming food systems in Africa

by Sheryl L. Hendriks, Endashaw Bekele, Thameur Chaibi, Mohamed Hassan, Douglas W. Miano and John H. Muyonga

As recognised by the Science, Technology and Innovation Strategy for Africa – 2024 (STISA-2024), science, technology and innovation (STI) offer many opportunities for addressing the main constraints to embracing transformation in Africa. Preparation for the Summit provides an important moment for shaping the region's future and ensuring that the much-needed agriculture-led growth and development agenda can simultaneously deliver on improving nutrition and health, saving lives and curbing public health expenditure on nutrition-related diseases. Yet, the Comprehensive Africa Agricultural Development Programme (CAADP) and its associated national plans still need to adopt a food systems lens. As food systems need cross-sectoral coordination beyond what CAADP coordination is needed, institutional innovation is essential for Africa to rise to the vision of the AUC Agenda 2063 and the Food Systems Summit's aspirations.

This brief seeks to identify the opportunities for African countries to take proactive steps to harness the potential of agriculture and food systems to ensure future food and nutrition security by applying STI solutions. The potential applications cover essential STI solutions to a) improving production systems and restoring degraded systems (including soil quality); b) innovation in the processing and packaging of foods; c) improving human nutrition, health and productivity; d) addressing fragility and instability and e) greater access to information and transparent monitoring and accountability systems. Change will need to be supported by institutional coordination; clear, food safety and health-conscious regulatory environments; greater access to information and transparent monitoring and accountability systems. Mechanisation and digitisation will speed up such transformation and enable more inclusive advancement of food systems. ICT solutions and advances could play a significant role in advancing food systems and addressing inequalities in access to inputs, knowledge and markets. Adaptation through sustainable intensification and agricultural diversification may have to be combined with the creation of off-farm opportunities, both locally and through strengthened rural-urban linkages. Financial support (microfinance, credit, subsidies, loans, insurance, etc.) plays an important role in risk reduction for producers.

Introduction

The vision of the UN Food Systems Summit is to "launch bold new actions, solutions and strategies to deliver progress on all 17 Sustainable Development Goals (SDGs), each of which relies on healthier, more sustainable and more equitable food systems[1]" (UN, 2020). The Summit seeks to transform the way the world produces, consumes and thinks about food and build a just and resilient world where no one is left behind (UN, 2020, von Braun et al., 2021).

In response to growing interest in the role that agriculture and food systems can play in reducing malnutrition, addressing inequalities and reducing poverty, the Inter-Academy Partnership (IAP) embarked on a project to mobilise global Academy expertise to produce a global synthesis and four regional reports on the role of science, technology and innovation to transform the food and agriculture sector in Africa to be more resilient and sustainable systems and simultaneously improve nutrition and food security.

As recognised by the Science, Technology and Innovation Strategy for Africa – 2024 (STISA-2024) (AU, 2014a), science, technology and innovation (STI) offer many opportunities for addressing the main constraints to embracing transformation in Africa. This

1 Food systems encompass all the elements and activities that relate to the production, processing, distribution, preparation and consumption of food, as well as the output of these activities, including socio-economic and environmental outcomes (HLPE, 2020). "Sustainable food systems are: productive and prosperous (to ensure the availability of sufficient food); equitable and inclusive (to ensure access for all people to food and to livelihoods within that system); empowering and respectful (to ensure agency for all people and groups, including those who are most vulnerable and marginalized to make choices and exercise voice in shaping that system); resilient (to ensure stability in the face of shocks and crises); regenerative (to ensure sustainability in all its dimensions); and healthy and nutritious (to ensure nutrient uptake and utilization)" (HLPE, 2020).

brief summarises and updates the IAP report entitled Opportunities and challenges for research on food and nutrition security and agriculture in Africa (NASAC, 2018) as a contribution to the Summit. The IAP/NASAC report (NASAC, 2018) updated an earlier perspective set out by the InterAcademy Council's (IAC) 2004 report on Realizing the Promise and Potential of African Agriculture. This earlier report set out recommendations and proposed approaches and actions to deploy STI to more effectively improve agricultural productivity and food security in Africa (InterAcademy Council, 2004) as commissioned by the United Nations Secretary-General, the late Kofi Annan.

The 2018 IAP/NASAC report and this brief seek to support the preparation of African governments and stakeholders to simultaneously achieve the vision of the Summit along with achieving the 2014 Malabo Declaration on the Comprehensive Africa Agricultural Development Plan (CAADP) (AU, 2014b), Africa's Agenda 2063 (AU, 2009) and their SDG commitments. In July 2020, a Joint Ministerial Declaration and Action Agenda (AU, 2020), called "upon [African] governments and partners to commit adequate resources to build greater productive capacity in agriculture, strengthening resilience in Africa's agri-food systems through the allocation of new resources or repurposing existing public resources".

Preparation for the Summit provides an important moment for shaping the region's future and ensuring that the much-needed agriculture-led growth and development agenda can simultaneously deliver on improving nutrition and health, saving lives and curbing public health expenditure on nutrition-related diseases. This includes addressing the usual elements of undernutrition and widespread micronutrient deficiencies (termed "hidden hunger") and the growing problem of overweight and obesity that is increasing across the African continent. This brief seeks to identify the opportunities for African countries to take proactive steps to harness the potential of agriculture and food systems to ensure future food and nutrition security by applying STI solutions. It should be noted that the biotechnology revolution arose from the convergence of advancements in the biological, physical, engineering, and social sciences. In terms of food systems, what converges is the technical reinforcement of these advancements in terms of product optimization and formulation and the n mutual benefit of different disciplines. Food systems approaches will bring about new innovations from transdisciplinary perspectives to solve unique problems.

The context of African food systems

Agriculture is at the core of almost all African economies (Baumüller et al., 2021). However, most AU Member States were not on track towards achieving the 2014 Malabo Declaration and CAADP goals and targets by 2025 (AU, 2020). As the Malabo Declaration targets overlap with the Sustainable Development Goals (SDGs), particularly SGD2, Africa is lagging on achieving the goals. The recent COVID-19 pandemic has been a setback in terms of progress towards reducing hunger and malnutrition.

African food systems are diverse and draw on several traditional and modern technologies. Agriculture (including crop production, animal husbandry, fisheries and forestry, and the manufacturing and their processing) can stimulate economic growth and enhance economic transformation in Africa through rising rural incomes, creating jobs, increasing government revenue, and ensure accelerated economic growth and development (Baumüller et al., 2021). Increasing producers' and processors' incomes can positively affect poverty reduction and food security and nutrition (Baumüller et al., 2021). Furthermore, the recently introduced African Continental Free Trade Area (AfCFTA) agreement offers many opportunities for the development of food systems, including diverse livelihoods across the food system and the provision of safe and nutritious food to all on the continent using Africa's own resources and reducing the reliance on imports and development assistance.

Africa will require radical actions to reduce undernutrition, correct micronutrient deficiencies and simultaneously stem the tide of increasing overweight and obesity. Africa had the highest regional undernourishment rate in 2019 (19.1% or more than 250 million undernourished people), more than twice the world average and growing faster than any other region (FAO et al., 2020). The proportion of people undernourished has risen by 1.5% since 2014 and is projected to rise to 25.7% by 2030 (FAO et al., 2020). More than 675 million people in Africa were food insecurity (as measured by the Food Insecurity Experience Scale of FIES) in 2019 (FAO et al., 2020). Recent economic slowdowns and downturns partly explain the increase in hunger in several parts of sub-Saharan Africa (FAO et al., 2020). The COVID-19 pandemic and other emerging diseases have worsened the situation, increasing the poverty of resource-poor food producers, particularly in already fragile regions.

While African agriculture growth has accelerated, growth through innovations (i.e. total factor productivity growth) lags behind other regions of the world (Baumüller et al., 2021). Africa imports large amounts of food - US$ 60 billion per annum (UNCTAD, 2020) - to fill supply gaps. Bouët et al. (2020) report that in net terms, this amounts to about US$ 25 billion per year in cereals, US$ 8 billion in meat and dairy, US$ 4 billion in sugar and US$ 9 billion in the vegetable oil sector. Many African countries' over-reliance on imports to meet the local demand for staple foods renders these economies vulnerable to many risks, insecurities, and uncertainties. While importing staple food is not negative per se, disproportional reliance on external sources for food is a risk that threatens long-term resilience.

It is estimated that by 2050 Africa's population will increase 2.5-fold (Suzuki, 2019) and the demand for cereals is likely to triple (van Ittersuma et al., 2016). The region's rapid population growth is attributed to rising life expectancy and declines in death rates, particularly of children (Jayne and Ameyaw, 2016). This will have consequences for agriculture and food systems, including pressure on land, water and other natural resources. Land prices may rise as a result (Jayne and Ameyaw, 2016). The population below the age of 24 years accounts for the largest share of the population in almost all countries in Sub-Saharan Africa (World Bank and IFAD, 2017). The World Bank and IFAD (2017) report that an estimated 440 million young people will enter Africa's rural labour market by 2030. Future demographic trends will influence labour and land productivity and youth needs will need to be factored into future development planning and STI applications (World Bank and IFAD, 2017).

Price and affordability are key barriers to accessing sufficient, safe, nutritious food (Herforth et al., 2020). Food prices and low incomes constrain access to adequate diets for many people in Africa. The FA0 (2020) reported that 829 million of the three billion people in the world who could not afford a healthy diet in 2019 lived in sub-Saharan Africa. Just more than 12 % of people in Africa could not afford a calorie-sufficient diet in 2019. While 56.4% were not able to afford a nutrient-adequate diet and 80.0% could not afford a healthy diet (Herforth et al., 2020). While local prices vary significantly by location and across seasons, the costs of perishable and nutrient-dense foods contribute significantly to the total cost. Yet, these foods are essential to overcome undernutrition and micronutrient deficiencies.

The COVID-19 pandemic (like others in the past) has disrupted food systems and livelihoods in Africa and threaten the significant gains over the past few decades in African development. The pandemic has led to transport restrictions and quarantine measures that restrict farmers' access to input and output markets and services, including human and animal health services (MaMo, 2020). While data suggests that Africa has largely been spared of the pandemic's scourge (Maeda and Nkengasong, 2021), the long-term impacts are yet to unfold.

Food systems transformation is required to ensure adequate incomes for producers and enable access to affordable, healthy diets[II] while managing increasing food demand from growing and rapidly urbanising populations. Yet, CAADP and its associated national plans still need to adopt a food systems lens. As food systems require cross-sectoral coordination beyond what was needed for CAADP, institutional innovation is also needed for Africa to rise to the vision of the AUC Agenda 2063 and the Food Systems Summit's aspirations.

Transforming food systems in Africa through STI

Science has the potential to find sustainable solutions to challenges facing food systems that relate to health, nutrition, agriculture, climate change, ecology and human behaviour (IAP/NASAC, 2018). As many African economies are still largely agriculturally based and many African value chains under-developed, adopting an integrated approach to developing and advancing food systems

II A healthy diet is health-promoting and disease-preventing. It provides adequate nutrients (without excess) and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances (Neufeld et al., 2021).

could provide multiple opportunities for the development of African economies and societies.

With her rich diversity of production systems, significant biodiversity and strong cultural association with traditional diets that are for the most part nutritious and healthy, the development of Africa's food systems have the potential to build healthier, more sustainable and more equitable food systems when supported by advances in technologies and research. Any change in food systems will lead to a multiplicity of changes (either positive or negative) affecting nutrition, health, welfare and the environment. The health implications, welfare outcomes (such as through livelihood outcomes, wages and incomes) and dietary patterns' environmental footprints are strongly dependent on how foods are produced and processed. STI can help support food system development in ways that protect resources, provide livelihoods opportunities and improve incomes across the system and at the same time, deliver more nutritious and healthy diets. The following subsections provide some examples of how STI can support the Summit vision and progress towards the SGDs and Africa's Agenda 2063.

A. Improving production systems and restoring degraded systems (including soil quality)

Improving the efficiency of production systems is necessary given constraints on land and resource availability and the relatively small land plots in most of Africa (Lowder et al., 2016). Improving production efficiency is necessary to meet the growing demand for food (including animal-sourced foods) but is also an environmental imperative. The Food Systems Summit calls for a shift to nature-positive production systems that seek to build food systems that meet the fundamental human right to healthy food while operating within planetary boundaries that limit the natural resources available for sustainable exploitation.

Modernisation can positively influence the basket of food at the household level (such as foods for local consumption rather than export and foods with a relatively high nutritional value) that households produce or can access economically. Meeting this changing consumer demand will require substantial private investment to increase productivity in agri-food value chains, add value, enhance labour productivity, and create jobs to produce the food demanded by consumers (FAO, 2015a).

Soil fertility. Declining soil fertility is a major constraint to agricultural transformation in Africa (Jayne et al., 2019). Continuous cropping and unsustainable cultivation practices driven by shrinking farm sizes and increasing food demand threaten future food supply in Africa (Jayne et al., 2014), limiting the potential benefit from yield gains offered by plant genetic improvement (Tittonell and Giller, 2013). Appropriate soil improvement practices and informed production choices are essential to prevent further degradation. A holistic and integrated strategy is needed that focuses on raising organic matter and improving moisture retention (Kihara et al., 2016). The soil microbiome affects how plants react to environmental stresses such as high salinity and low water availability and diseases (Nadeem et al., 2014; Spence et al., 2014; Qin et al., 2016). The isolation of microbial strains and modern high-throughput sequencing technologies are being used to catalogue microbial species associated with plants in different soils, including arid and saline soils (Wild, 2016). The development of next-generation crop varieties should simultaneously select beneficial characteristics in the plant and the microbiome to improve soil fertility and crop yields (Gopal and Gupta, 2016). Research is also needed to develop protective seed coatings to protect plants from soil-borne pests and pathogens while also providing micro bio-fertilisers (Rocha et al., 2019).

Water. Water is needed for food production, food processing and industrialisation as well as safe drinking water, sanitation and hygiene. The demand for these resources competes for the available water that can be eased through use of appropriate technology and policy. Urbanisation will place increased pressure on the water demand and compete with water for the production of food. Urbanisation and industrialisation also pose threats to water quality.

Many energy-generation systems also depend on water sources for hydroelectric power, cooling power plants and hydraulic fracturing. Many countries with large-scale irrigation programmes source water from aquifers, threatening long-term sustainability, possibly leading to conflict over water in the future. Competition for water needs to be eased using appropriate technology and policies to protect and manage water resources (including river basins and lakes). Water-harvesting and storage are necessary to support crop and livestock production. More innovation is required in recycling wastewater to increase the overall availability of water. The desalination of seawater offers one option to increase the availability of water for human consumption and agricultural production. However, this technology is still expensive and results in waste (high salt concentrations) pose additional environmental problems (Ahmadi et al., 2020).

Investment and innovation will be necessary for low-cost yet efficient irrigation options to mitigate the impact of water scarcity and expand the availability of diverse foods year-round. Hydroponic production with recirculation of water and nutrients in a closed system can reduce water consumption (Al Shrouf, 2017). These systems also allow the containment of plant diseases, particularly viruses, in tropical regions. For example, drip irrigation delivers just the right amount of water, at a specific time, to a precise spot from where the water will be best absorbed by the plant, producing "more crop per drop". Promoting the use of renewable energies in water desalination for agriculture use could offer competitive cost options for the delivery of modern energy and increase the use of non- conventional water resources to guarantee long-term food security and socioeconomic stability.

Livestock. Livestock is an important element of millions of people's livelihoods in Africa's pastoralist, mixed crop-livestock farming and commercial systems, offeringmultiple opportunities for income and employment. Increases in demand for animal products in African countries outpace supply. Meeting this demand will require substantial increases in production while reducing the environmental footprint of livestock production. Livestock (including poultry, swine, sheep, goats, cattle and rabbits) are good sources of high-quality animal protein with rich amino acid profiles (NASAC 2018). They also provide much needed nutrient-dense foods, vital to overcoming the high rates of child malnutrition in Africa.

However, globally livestock accounts for 14.5% of all greenhouse gas emissions (cattle for 60% of these), with emissions linked to food digestion and feed production dominating emissions from ruminants (Gerber et al., 2013), and about a third of the freshwater footprint for agriculture (Mekonnen and Hoekstra, 2012). Although Africa's livestock sector is still primarily extensive (rather than intensive industrialised production), this may change as the demand for animal-sourced foods increases with shifting urbanisation and changes in income in middle-income countries. Climate change could affect future grazing capacities, lead to more migration of animal herds, and increase zoonotic diseases incidence (MaMo Panel, 2020).

Livestock genetic improvement programmes, interventions to increase carbon sequestration in grasslands and improved management of grazing lands could significantly increase productivity and reduce greenhouse gas emissions (Gerber et al., 2013; Henderson et al., 2015). The use of high-quality forage grasses and legumes offers a wide array of benefits, including higher livestock and crop productivity, restoration of degraded land through the accumulation of organic matter in soils, and improvement of soil fertility through the fixation of atmospheric nitrogen and the inhibition of nitrification in the soil and a year-round supply of feedstock (Rao et al., 2015). Indigenous feed resources can be incorporated into feeds to promote self-reliance. The available genetic variability of forage plants is still largely untapped and largely underutilised (Sandhu et al., 2015). Drought-tolerant *Brachiaria* grasses originated primarily in natural grasslands in Africa, yet they have only recently been re-introduced for commercial cultivation in African countries at a significant scale. It has been estimated that cows reared in Brachiaria pastures could increase by up to 40% in Kenya and Rwanda than native grasslands with spillover benefits further down the value chain (Maina et al., 2016).

Emerging challenges in animal health include improving resistance to disease and combating the misuse of antibiotics in animal production systems (Kimera et al., 2020). An example of such pests is the trypanosome parasites. Trypanosomiasis greatly restricts cattle rearing in 32 countries of Sub-Saharan Africa, leading to losses due to lost animals and animal products of between US$1 billion and US$6 billion annually (Yaro et al., 2016). The development of conventional vaccines against the parasite has been thwarted by trypanosomes' ability to continuously change the antigenic properties of their surface coat and evade attack by the host's immune system (Radwanska et al., 2008). The discovery of innate resistance to trypanosomiasis in some African wild animals is linked to the presence of a protein in their blood that kills trypanosomes, called APOL1, has opened new avenues of research (del Pilar Molina-Portela et al., 2005), offering opportunities to develop effective vaccines.

Fish is an important source of food and nutrients as well as livelihoods in Africa. Fish provides 19% of animal protein in African diets (Chan et al., 2019). Africa is a net importer of fish (Chan et al., 2019). A threefold increase in production is needed to meet expected demands in fish (Chan et al., 2019). Aquaculture, an emerging sector in the continent, holds great potential for rapidly increasing the amount of available protein. Aquaculture production in Africa expanded at an average annual rate of 11.7% between 2000 and 2012 (nearly twice the global average rate of 6.2% (FAO, 2014a). Given the spatial and environmental constraints, this will require improvements in efficiency, husbandry and increased investment in domestication and development of new species for commercial production alongside the genetic improvement of existing commercial stocks. Initiatives to genetically improve fish for aquaculture have so far been quite limited. Of the 400 species cultured, 90 are domesticated, and of these, only 18 (5%) have been the subject of significant genetic improvement programmes (Teletchea and Fontaine, 2014). Genetic improvement can also reduce the environmental footprint of aquaculture. For example, a study that investigated the environmental consequences of genetically improving growth rate and feed conversion in an African catfish established that increases in feed conversion reduced the environmental footprint in all the scenarios tested (Besson et al., 2016). On the other hand, improving growth rates had a beneficial environmental impact only when rearing density limited farm production. Both improvements raised farm productivity (Besson et al., 2016). These results indicate that determining the genetic basis of feed efficiency in fish with potential for commercial production in Africa is an important research objective, but they also show that breeding programmes need to be complemented by studies to improve feed quality and establish the best management practices to maximise productivity sustainably.

Optimising the utilisation of indigenous crops, livestock, fish and underutilised foods. Africa has over 2,000 plant species that include domesticated and semi-domesticated native grains, roots, fruits and vegetables. These are considered to be "lost" species for rediscovery and exploitation in modern food systems owing to their natural health and nutritional benefits and a variety of adaptive and resilient properties (National Research Council, 1996). Many indigenous crops have multiple edible parts such as leaves, fruit, seeds and roots. Many indigenous African livestock, fish and plant breeds are resilient to many risks and adverse growing conditions (Mabhaudhi et al., 2019). but are viewed as famine foods, foraged and turned to by the poor in adverse situations. Yet, many of these foods are described as 'superfoods'. Optimal utilisation of nutritious indigenous and traditional foods holds the potential for diversifying Africa's food systems, especially if more of these can be domesticated and produced in larger quantities. Yet, many highly nutritious African indigenous crops are threatened with extinction. On their own or included in existing monoculture cropping systems, these crops could support more sustainable, nutritious, and diverse food systems in marginalised agricultural environments (Mabhaudhi et al., 2019). There is a need to collect and categorise these underutilised crops and wild populations of important plant species and combine these with modern molecular breeding technologies.

There is an urgent need to create pride and demand for these foods and investment in research and technology development across the food system to integrate these resources into the daily food basket of African communities. The New Nordic Cuisine (Nordic Council, undated) food movement provides an example of how traditional food values can be revived and cuisine modernised and developed to give a renewed appreciation of the wealth of indigenous and traditional foods of high nutritional and health value.

Although not widely adopted in Africa, *biotechnology (techniques to improve plants, animals, and microorganisms) offers many opportunities* to improve productivity, overcome abiotic (such as drought) and biotic stresses (diseases and pests), and save time and effort for farmers in Africa. For example, genetically modified crop varieties are labour-saving and reduce agricultural production's drudgery—especially for women who are often tasked with more labour-intensive tasks such as weeding (Gouse et al., 2016).

Biotechnology can support food security in the face of major challenges such as declining per capita availability of arable land; lower productivity of crops, livestock and fisheries, heavy production losses due to biotic (insects pests, weeds) and abiotic (salinity, drought, alkalinity) stresses; significant postharvest crop damage and a declining availability of water. Biotechnology techniques that could be applied include tissue culture; marker-assisted selection, which entails the development of genetic markers to fast track selection of natural traits in plant breeding the "omics" (sciences such as genomics, and proteomics and transcriptomics); the development of diagnostics; genetic modification; and a newer set of tools collectively referred to as the new plant breeding technologies (NASAC, 2018). Some examples of the application of biotechnology in Africa include the development of disease-resistant bananas and cassava; vitamin enriched bananas and nitrogen-efficient rice in Uganda (Ainembabazi et al., 2015; Wagaba et al., 2016); insect tolerant cowpea in Nigeria, Niger and Ghana; and drought-tolerant maize in Kenya (Mohammed et al., 2014; Muli et al., 2016). Tissue culture can play an important role in producing disease-free planting material for vegetatively propagated crops such as banana and cassava (Akin-Idowu et al, 2009; Kikulwe et al., 2016) and is an essential tool for the conservation, improvement and mass production of African indigenous crops (Opabode, 2017). Marker-assisted selection has been used successfully to improve a variety of traits in crops in crops such as drought-tolerant maize varieties (Beyene et al., 2016), Striga resistant cowpeas in Nigeria and sorghum in Sudan (Omoigui et al., 2017; Ali et al., 2016). Marker-assisted selection has also been applied to developing crop varieties with higher nutritional contents (Andersson et al., 2017).

New advances in science offer opportunities for the development and mass production of microbes and microbial enzymes to enhance the quality and efficiency of feed processing and utilisation in the gut microbiome of livestock, which plays a crucial role in animal digestion and the resulting level of emission of greenhouse gases (O'Callaghan et al., 2016).

B. Innovation in the processing and packaging of foods

Transformation of the food system in Africa demands that we harness STI 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 postharvest losses (including aflatoxin) and food waste (Hendriks and Covic, 2016). These solutions should consider current changes in demand, predict future demand changes, and shape the African food system's future in ways that will provide nutritious food for all.

Preserving food and reducing food loss is an imperative part of an efficient and sustainable food system. The growth of the middle-class and increased urbanisation are likely to increase demand for processed foods. However, limited and unreliable electricity supply may constrain the wide adoption of such technologies. Access to energy is crucial for the transformation of Africa's food systems and has a transformative impact on the livelihoods of the rural poor, reducing the drudgery of their work and generating higher incomes (MaMo Panel, 2019a). Many options are emerging that Africa could benefit from in terms of off-grid and mini-grid technologies for hydro, wind, and solar power.

Postharvest handling and technologies offer opportunities to reduce food losses and waste, particularly in the African context where cold chains and refrigeration are largely missing (MaMo, 2019b) and seasonality leads to gluts and shortages of perishable goods. Many of these losses can be prevented through proper training and handling of goods, adopting appropriate tools or technologies, sound policies and marketing-related improvements (Statherset al., 2020). More investment is also needed in developing and making available solar driers and agro-processing equipment such as shellers and de-pulpers.

Food processing has the potential to contribute to the reduction of postharvest losses, enhancement of food safety and quality, creation of diversity, and stabilisation of food supply, reducing the prevalence of seasonal hunger and improving market access. Food processing can generate jobs and increase the retention of organic waste in farming areas. Even simple processing methods can transform perishable crops into a range of convenient, storable, value-added products, which meet the needs of expanding markets (Muyonga, 2014). Processing foods may smooth supplies but can create deleterious health consequences (overweight, obesity and non-communicable diseases) depending on their ingredients (trans fats, high sugar and sugar alternatives and excessive preservatives and other additives) (Pot et al., 2017). On the other hand, processing can also be used to create products that address specific nutrition needs. By blending staples and foods with complementary nutritional value and applying suitable processing procedures, it is possible to develop nutrient- and energy-enhanced foods to supplement prevailing nutritionally inadequate diets, which are particularly important for infants and young children.

Food safety is critical to the advancement of foods systems. Poverty exacerbates the problem since it leads to overdependence on one foodstuff and may lead to the consumption of contaminated foods because of the lack of alternatives (Shephard and Gelderblom, 2014). Evidence on foodborne disease (FBD) in low and middle-income countries (LMICs) is still limited, but important studies in recent years have broadened our understanding. Grace (2015) reports that most of the known burden of FBD disease in low and middle-income countries comes from biological hazards, primarily from fresh, perishable foods sold in informal markets (Grace, 2015). Testing is often expensive and constrains the approval, distribution and export of foods. The lack of suitable regulations to prevent food contamination, or their poor enforcement when regulations exist (often applied to export goods, but not the domestic market) combined with the low levels of capacity for detecting food toxins, are serious concerns (Matumba et al., 2017). Rapid and cheap out-of-laboratory analytical techniques designed for field conditions can offer solutions to these problems (Shephard and Gelderblom, 2014). An example is fluorescence spectrophotometry for quantifying mycotoxin levels in grains and raw groundnuts (Shephard, 2016) and the Lab-on-Mobile-Device (LMD) platform that can accurately detect mycotoxins using strip tests (Dobrovolny, 2013).

More research and development is needed in packaging solutions to extend the shelf life of food, thereby reducing enzymatic activity and the growth of microorganisms and preventing moisture loss and decay. Thermal processing has been widely employed in the food industry for food safety assurance and extending product shelf-life by inhibiting or inactivating microorganisms (Caminiti et al., 2011; Stoica et al., 2013). Other technologies that could have significant benefits for food safety in Africa include non-thermal inactivation technologies such as electromagnetic fields, pulsed electric fields, high-voltage discharge, pulsed light, ionising radiation, microwaves and cold plasma (NASAC, 2019). Hybrid technologies and combinations of these methods have not yet been applied to the indigenous food industry but could hold promise for transforming African food systems.

National agro-processing strategies and interventions are needed to meet the anticipated rise in demand for these foods. Some possible interventions include establishing agro-processing incubators, promoting local production of food packaging materials, provision of fiscal incentives, and promoting research aimed at developing appropriate processing technologies.

C. Improving human nutrition, health and productivity

Making more nutritious food options available to a wide range of consumers is another pathway to influencing nutritional outcomes. This can include public and private sector investment in research and innovation of technologies and processes that improve foods' nutritional value. Recent advances in gene sequencing technologies enable investigation of the complex gut biome at both the genetic and functional (transcriptomic, proteomic and metabolic) levels and can map microbiome variability between species, individuals and populations, providing new insights into the importance of the gut microbiome in human health. Together with studies of traditional diets that include a wide range of herbal, medicinal and fermented products from Africa's wealth of indigenous foods, these offer opportunities for understanding how foods and the gut biome interact to protect human health and immunity.

Food fortification initiatives such as salt iodisation, adding vitamin A to cooking oil and multivitamin mixes to maize flour, as well as the bio-fortification of crops such as the varieties of vitamin-A-enriched orange-flesh sweet potato, offer options for reaching a high proportion of the population. More research is needed into which African crops could benefit from breeding programmes for biofortification to diversify the food basket and preserve the genetic diversity of nutritious traditional crops. Breeding, processing and additives such as prebiotics and probiotics offer the potential for enhancing the bioavailability of nutrients for absorption and metabolism (Markowiak and Śliżewska, 2017) or decreasing the concentration of antinutrient compounds that may inhibit the absorption of nutrients (for example, phytates and oxalates) (Popova and Mihaylova, 2019).

Advances in gene sequencing technologies enable investigation of the complex gut biome at both the genetic and functional (transcriptomic, proteomic and metabolic) levels. They can map microbiome variability between species, individuals and populations, providing new insights into the importance of the gut microbiome in human health (Brunkwall and Orho-Melander, 2017). Together with studies of traditional diets that include a wide range of herbal, medicinal and fermented products from Africa's wealth of indigenous foods, these offer opportunities for understanding how foods and the gut biome interact to protect human health and immunity.

D. Addressing fragility and instability

Climate change and increasing competition for key resources such as land and water provoke violence and armed conflicts, exacerbating the vicious circle of hunger and poverty (FAO et al., 2020). Conflict disrupts food production, blocks the flow of food and humanitarian aid, and drives food prices beyond the level of affordability (NASAC, 2018). COVID-19, climate change, conflict (including that between farmers and herdsmen) and protracted crises could increase hunger and child malnutrition and reverse the gains achieved over the past two decades. As part of the broader considerations for local-global interconnectedness in food systems, future food production must be achieved with a lower impact on the environment (German et al., 2016) and more efficient use of inputs and land.

Addressing these critical challenges will require an integrated approach that deals with issues about the sustainable use of natural resources (including water, energy, soils); increasing the productivity of crops and livestock; expanding the number of species used for food production to include neglected indigenous crops, and promoting diversification in livelihood activities. Environmental protection is essential for preserving the production potential of agriculture in Africa.

E. **A data revolution for greater access to information and transparent monitoring and accountability systems**

The complex nature of food systems demands transdisciplinary collaboration and inter-sectoral governance. ICT can enhance learning between stakeholders in the system as well as between disciplines to support innovation and the emergence of practical technologies that arise from transdisciplinary collaboration.

Evidence-based policies and planning require extensive and up-to-date data. There is an urgent need to strengthen national and regional institutional capacities for knowledge, data generation, and management that support evidence-based planning, implementation, and monitoring and evaluation (Bahiigwa et al., 2016). ICT innovations also offer multiple opportunities for improving and optimising food systems that could support the establishment of "big data" systems, analysis and reporting of cross-sectoral data, and monitoring and evaluation of implementation. Therefore, more significant investment is needed in more and better data, and inclusive annual national and subnational reporting mechanisms need to be developed and implemented to assess progress on commitments for food security and nutrition outcomes and actions in a timely way (Hendriks and Covic, 2016).

Collecting, managing and reporting data requires extensive information systems. "Big data" systems offer opportunities to analyse vast datasets to reveal patterns, trends and associations, especially in multi-sectoral applications such as those seen in the SGDs and national performance and monitoring situations related to food systems through innovative approaches and algorithms. Some applications include fraud and risk detection, logistic planning in programmes and price comparisons, as well as predictive and proactive health disease and health management systems (NASAC, 2018).

Public awareness of the problems, hazards and solutions is essential. Cloud computing allows for crowdsourcing and the active participation of citizens in mutual accountability systems and the provision of highly disaggregated geo-referenced data that can play an important role in monitoring contexts such as climate change, disease patterns and early warning systems. Communication science offers opportunities for exploring how to deploy digital media and improve communication systems to share knowledge at all levels.

The role of ICT in rapid identification of pests and diseases and mapping of their locations and spread are important tools for managing and mitigating risks due to the spread of pests and diseases (Christaki, 2015) and for increasing the awareness and preparedness of farmers, especially as much of the African food chain is informal. Investment in qualified staff within government, extension, and supporting research institutes is crucial, with a particular need for investment in young researchers and entrepreneurs. Comprehensive soil mapping is necessary to address the deficiencies through appropriate soil improvement practices and the cultivation of the most suitable crops for each area. Overlaying these with weather and crop suitability maps can provide hands-on information to farmers through mobile technology. Mobile technology could be used to improve early warning systems and dissemination of knowledge. One example is the Participatory Integrated Climate Services for Agriculture, which can help farmers make informed decisions based on accurate, location-specific, climate and weather information combined with the locally relevant crop, livestock and livelihood options, and participatory tools (Dayamba et al., 2018).

Satellite Earth Observations as a novel opportunities of the ICT revolution, combined with in-situ data, provide a source of consistent and reliable information to benefit the water, energy, and food Sustainable Development. Such observations are necessary to begin understanding the complex feedback processes between the natural environment and human activities (FAO, 2014)b.

ICT can solve many of the current constraints about access to information, data analysis, predictions and early warning. Innovations in mobile technology can overcome many trade and market-related information challenges, link farmers to markets and provide two-way communication between producers, consumers and researchers. ICT applications and advances in digital banking offer opportunities for solving some of these constraints.

However, African countries need to invest in capacity building, including STI research and development; training and education; communication; monitoring and evaluation; and governance and building international collaborations. Clear long-term commitment and funding (for both infrastructure and human capacity) are crucial to attaining targets such as improving production and food systems. Additional capacity for biotechnology is necessary in Africa, particularly to build a critical mass of expertise that can select, diffuse, adapt and use technologies from abroad.

Concluding messages

STI offers many promising opportunities for agricultural transformation in Africa. Modern science can unlock the potential and protect the heritage of Africa's nutritious food sources and ensure sustainable and diverse diets. Changing the path of future food systems in Africa will demand a structural transformation (transitioning from low productivity and labour-intensive economic activities to higher productivity and skill-intensive activities) of food systems and considerable value chains development. The mandate and operations of S&T institutions are necessary to enhance their contribution to the exploitation of S&T for sector transformation.

The context-specific essential STI solutions relevant to transforming food systems in Africa relate to:

a) improving production systems and restoring degraded systems (including soil quality);

b) innovation in the processing and packaging of foods;

c) improving human nutrition, health and productivity;

d) addressing fragility and instability and

e) greater access to information and transparent monitoring and accountability systems.

The Food Systems Summit offers opportunities for stakeholders in African food systems to reflect on the role STI can play in transforming food system outcomes to improve the supply of safe and nutritious food for all while restoring and protecting the degradation of natural resources to ensure the sustainability for future generations.

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The Role of Science, Technology, and Innovation for Transforming Food Systems in Asia

by Paul J. Moughan, Daniel A. Chamovitz, S. Ayyappan, Morakot Tanticharoen, Krishan Lal and Yoo Hang Kim

This brief focusses on the role of science, technology and innovation (STI) in transforming the food systems of Asia and the Pacific to achieve long-term environmentally sustainable food and nutritional security, and draws upon the findings of a recent Association of Academies and Societies of Sciences in Asia (AASSA) Working Group. The Working Group included scientists appointed by the respective academies and from across the region and representing different relevant scientific disciplines.

The Working Group recognised that a "whole of systems" approach is required to address the issue, and that work is urgently needed to define 'healthy' diets for different regions, societies and cultures. Emphasis should shift from the provision of calories, to the supply balanced patterns of all the essential nutrients, and the 'holistic' properties of foods should be recognised.

The AASSA study identified countries and regions, within Asia, considered to be at particularly high risk for future food security. It was urged that systems analysis be applied across the agricultural and food sectors of these countries to identify the actual technical and other impediments to food and nutrients supply. It was envisaged that the results from such an analysis would be used to formulate a 'blueprint' for agricultural and food STI in Asia.

Overarching recommendations were the establishment of a trans-national funding mechanism for the entire region focussing on targeted inter-disciplinary STI, and the establishment of regional Centres of Excellence for research, education and extension focussing on the identified key areas of opportunity.

It was concluded that there is an urgent need for investment and action.

Introduction

It is now widely accepted that there is an imperative to transform food systems to provide guaranteed supplies to all of nutritious, healthy foods that are produced and distributed in a sustainable manner, for a rapidly growing world population (Committee on World Food Security (CFS), 2019; FAO and WHO, 2019; Fanzo et al., 2020a; Global Panel on Agriculture and Food Systems for Nutrition, 2020; GNR, 2020; International Food Policy Research Institute (IFPRI), 2020a).

A consensus view is one thing, but what is now required is Action.

This briefing document focusses primarily on the role of science, technology and innovation (STI), and including research and development (R&D), education and extension, in transforming the food systems of Asia and the Pacific. The briefing draws heavily on the IAP report published in 2018: "Opportunities and challenges for research on food and nutrition security and agriculture in Asia", but updated to included new perspectives. The Working Group responsible for the latter report was convened under the auspices of the Association of Academies and Societies of Sciences in Asia (AASSA). The approach was a "bottom-up" analysis of projected food and nutrition security in the region with respect to population growth and related demographics, projected regional trends in malnutrition in all its forms, climate change, resource depletion, biodiversity loss and environmental degradation. Experts from science academies across the region made up the Working Group, and each expert provided information and insight for their country or region. This allowed synthesis of the material to allow common themes to be developed and general as well as specific conclusions to be made. A strength of the inter-science academy approach was that expertise from a broad range of relevant scientific disciplines from across a wide geographical area, was drawn upon. This allowed the identification of scientific and technical issues and opportunities not only at global and regional levels, but also at a national and sometimes sub-national level, reflecting the great diversity between and within countries, sectors and populations.

The overarching framework for developing inclusive, sustainable food and nutrition systems

Globally, a considerably greater quantum of food and a more diverse array of food types, needs to be produced and distributed equitably to ensure a balanced diet to adequately nourish a projected population of around 9 million persons by year 2050. This is against a current backdrop where around 1 billion people are undernourished, many more suffer from 'hidden hunger' whereby they receive inadequate amounts of vitamins and minerals, and where in many countries, there is an escalating prevalence of obesity and the metabolic syndrome.

This required increase in the production of foods must occur in the face of several constraints. The land area available for agriculture is unlikely to increase in the future and may well decline because of the demands of urbanisation, conservation, bio-ecology and land loss from sea-level rises caused by global warming. Limitations in the supply of other vital resources (e.g. fossil fuels, fertiliser and water) are also likely to pose a challenge. Future food increases will need to be sustainable, environmentally, economically, culturally and socially, and will occur in the face of unpredictable outcomes that are consequent upon climate change. The 17 Sustainable Development Goals adopted by the United Nations in 2015 offer an important framework for addressing the challenge of the global food supply but, if these goals are to be met, evidence-based science will be a necessary prerequisite.

The production and supply of food follow a complex web of interacting processes and systems. Agriculture and food production are part of a widely interconnected multi-functional landscape or agri-ecosystem (German et al., 2017). To achieve sustainable production, the wider ramifications of changes to the systems need to be assessed and understood and inevitable trade-offs reconciled.

A systems analytical approach is paramount to identify impediments to FNS and to provide workable holistic solutions. A wide range of both technical and non-technical (including purchasing power, barriers to trade, capital investment, infrastructure, government policies, cultural mores, demographic shifts, political and social stability, equity of access, gender equality and education) factors is relevant. Not wishing to undermine the importance of these non-technical factors, it is beyond doubt that science, technology and related innovation (SIT) will be critical in addressing FNS. The production of food in a sustainable manner, the processing and storage of food, the minimisation of food wastage and the development of healthy diets adapted to local conditions and populations are of paramount importance. The application of current scientific knowledge through improved education and extension practices, the development of new scientific knowledge in targeted areas and related technology developments will all be essential in terms of meeting the global food challenge.

In the AASSA (2018) report on FNS for Asia, the need to focus STI efforts to provide high quality relevant evidence was emphasised, a contention echoed recently by the Committee on World Food Security (2019) and Fanzo et al. (2020b).

The approach taken by the IAP Working Group was to use national and regional statistics for Asia and the Pacific on projected population growth, population age distributions, economic development and current estimates of under- and over-nutrition to allow a focus on countries and geographical areas that are most likely in the future to face the harshest FNS issues. A strategy moving forward would be to use 'systems analysis' to identify key impediments to FNS in these areas and to use such analysis to prioritise extension, education and research and development (Stathers et al. 2020; Ricciadi et al. 2020). The report emphasises the need for a territorial dimension in such an analysis, recognising often profound differences between geographical areas and socio-economic groupings. The territorial approach to investigating FNS implies a shift from a sectoral (usually agricultural production), top-down, 'one-size-fits-all' approach to one that is multi-sectoral, bottom up and context specific. Food systems must be inclusive of marginalised people and small holders (IFPRI, 2020) as should STI and education.

The work has identified several countries within the region that are at high risk for future FNS. Countries such as India, Bangladesh, Pakistan, Afghanistan, Nepal and Myanmar as well as the Philippines, Tajikistan, Iraq and Yemen are deemed to be particularly high risk countries for future FNS. This is not to say that other countries in the region are free from future issues concerning FNS; rather, it gives a rational starting point as to where work may be most effective.

There is no doubt that the global and Asia food supply will be required to increase significantly over the next three decades. The required increase in net food supply may involve reducing food wastage and effects on the demand side brought about by changing food consumption patterns, but will also involve producing more food from existing agricultural land. This will involve both closing existing yield gaps and increasing food production from land that is currently considered to be yielding at a high level, through further intensification. Intensive agricultural production is already associated with environmental costs, however, through side effects such as nutrient runoff and eutrophication of waters, greenhouse gas (GHG) emissions, soil erosion and soil degradation, as well as resource costs such as depletion of water and fertiliser reserves. Future farm production will be expected to reduce these negative environmental impacts. 'Sustainable intensification' will be required, and this will require a step-change in STI (Pretty et al., 2010; Parker et al., 2014). China is already making progress in this domain (Cui et al., 2018) Clearly, increased production per plant or animal, in a sustainable manner is beneficial in that it reduces the amount of waste material (e.g. methane) per unit of production (e.g. kilograms of grain or kilograms of meat). Over recent years there has been a renewed interest in bioecological agriculture and circular agriculture, where an ecological harmony is sought, and resource use is optimised and solid wastes and gaseous emissions are minimised due to capture and re-use. Research in this direction is encouraged, though it is recognised that bioecological agriculture and intensive farming are not mutually exclusive systems. Traditional mixed framing models of intensive agriculture may already incorporate principles inherent in bioecological farming (eg crop rotations, animal/crop/pasture balance, the use of tree shelter belts, nitrogen fixation via leguminous crops and clovers, minimal tillage, integrated pest management).

Although the IAP Working Group strongly promoted the clear identification of gaps in knowledge, currently creating impediments to lifting and diversifying food production, as a critical starting point for renewed and refreshed STI effort, they also recognised that there are certain areas of contemporary science, whereby investment in R&D is likely to yield immediate and widespread dividends. These areas included: (1) sustainable farming practices addressing wider issues such as biodiversity, land and water degradation and climate change which would include bioecological approaches; (2) genomic-based approaches (including molecular markers for selection and CRISPR/Cas9 technologies) to plant and animal breeding; (3) 'big data' capture and analysis, precision agriculture, robotics, artificial intelligence; (4) Food technology innovations in harvesting, processing and storage to reduce wastage, and promote more equitable distribution of safe non-perishable food and lead to healthier processed foods; (5) Aquaculture production and integrated farm production systems.

Delivering healthy diets

In achieving FNS in the future, calorie provision alone will not be sufficient. Rather it will be required to provide a broad range of diverse foods so as to meet the requirements for all of the dietary nutrients, and non-nutrient food components known to influence human health. Just what constitute a healthy diet is a 'moving target', and research is required to establish scientifically what constitutes healthy diets for different socio-cultural groupings and regions. Currently, for example, there is controversy over the role of saturated fats in health (Bier, 2016) and over the risk of consuming unprocessed red meat for the development of bowel cancer (Alexander and Cushing, 2011).

The classical approach in nutritional science has been reductionist, whereby the nutrients found in foods are considered the fundamental unit of nutrition. This concept has been challenged more recently, and considering the clearly important 'holistic' properties of foods, it has been suggested that a food should be considered as the fundamental unit of nutrition (Kongerslev, et al., 2017). A better scientific understanding is required of the nutritional and health effects of the interactions of structures within complex food matrices and among foods when mixtures of different foods are eaten together. With such knowledge there is an opportunity to manufacture healthier foods. During traditional manufacturing natural food structures are often degraded, and new structures potentially with less desirable properties, formed. New approaches to food manufacturing are needed to ensure the provision of food matrices, food nutrient contents and food bioactives that are consistent with health. The food industry is clearly a powerful medium, for the manufacture and distribution of healthy foods and the way forward will be cooperative research programmes between agricultural sectors, food companies, universities and government funded research organisations to explore new processing technologies with the aim of shifting the food supply towards nutritious healthy foods and diets.

Having accurate information on the amounts of dietary nutrients required to support body processes and long-term health (dietary requirements) is insufficient. Foods also contain many compounds that are not classically viewed as nutrients (eg phytochemicals, bioactive proteins and peptides, and fibre), but may have important effects upon human health. Examples, among many, are immunoglobulins in milk, probiotics in yoghurt and other fermented foods, catechins in tea, bioactive peptides released from many proteins, flavonoids in cocoa, and tannins and anthocyanins in fruits and berries. These properties of food need to be much better understood, and should be the focus of STI. Moreover, the role of diets in influencing gene expression in humans (nutrigenomics) and how genetic makeup influences dietary effects on physiology, metabolism and health (nutrigenetics) offer great potential for a better understanding of nutrition and its influence on health, and pave the way for personalised nutrition (Fenech, 2008). It is important to recognise that it is not only the human genome that is influenced by and influencing nutrient uptake and metabolism, but the numerous genes of the prolific gut microbiome undoubtedly have a major influence on nutrient utilisation, metabolic outcomes and health. This is a fertile area for further research and highlights again the complexity of the influence of diet on human health.

There is much evidence that often poor nutritional choices are made at the point at which foods are selected for consumption, and better education at all levels on the impact of food and nutrition on health is critical. Sociological and behavioural research is required to better understand the purchasing motivation of people of different ages and socio-cultural backgounds. Foods must be desirable, and equally STI is needed to ensure the wide availability of foods that are not only nutritious and healthy, but are also safe, convenient, and that have great taste, texture and other properties. Food science and technology, including sensory science, have a major role to play.

In the IAP study particular attention was given to the Hindu Kush Himalayan (HKH) region, a vast area of land extending 3500 km across the high mountain regions of Afghanistan, Bangladesh, Bhutan, China, India, Nepal, Myanmar and Pakistan. Malnutrition and hunger are widespread in the region and a complex interaction of socio-economic, environmental (including food production systems) and cultural factors is considered to be the cause of the widespread malnutrition.

The mountain areas have a low 'carrying-capacity' for agricultural production, and cropping systems have been reliant on diverse traditional crop varieties. However, rapid socio-economic change has led to changed land use, changed crop varieties and new food consumption patterns. The planting of nutritious traditional crops, such as amaranth, buckwheat, minor millet, finger millet, proso millet, foxtail millet, sorghum, barley and sweet potato, is declining; these crops are being replaced by higher-calorie-yielding crops such as rice and wheat, leading to a decline in agro-biodiversity. The production of traditional crops is declining because of factors such as a lack of awareness of their nutritional value, a lack of local markets for the produce and an increasing demand for crops such as rice, wheat and maize. There has been a shift in foods from home-grown foods to purchased foods, from coarse-grain foods to fine-grain foods and from traditional snacks and drinks to potato chips, instant noodles and soft drinks (Rasul et al., 2017). The consumption of the traditional coarse grains is often viewed as backward in the new value system.

The trend by the urban poor away from legumes and coarse grains, and towards the consumption of oils, fats and high-sugar products, is not unique to the HKH region but is general in both China and India (Du et al., 2002).

Further, there would appear to be much scope for encouraging farming programmes among smallholder farmers that aim to diversify diets and improve nutrition. Such programmes (Girard et al., 2012) aim to increase household production of perishable nutrient-rich foods (e.g. fruits, eggs, meat, fish and milk). The production of such foods on the farm makes them accessible and less vulnerable to storage and transport losses. Such an approach has been shown to diversify the diet of often nutritionally vulnerable smallholders (Iannotti et al., 2009).

Transformation to sustainably produced and healthy diets

Not only must the diets of the future be healthy, but they must also be sustainably produced. A new approach is needed to design, evaluate and monitor diverse farming systems. The complexities of diverse farming systems need to be recognised and a nuanced approach taken (Global Panel on Agriculture and Food Systems for Nutrition, 2020). By means of example ruminant livestock farming makes a major contribution to GHG emissions, but at the same time livestock farming is economically and culturally important to many people. Also meat and milk are of high nutritional value and an important supply of minerals (such as calcium, zinc and iron) and vitamins, such as vitamin B12. Whereas a case may be made for the inefficiency of feed-lot cattle production (Poore and Nemecek, 2018), the same is not necessarily the case for large amounts of pastoral cattle production (Adesogan et al., 2019). Moreover, meat and milk are primarily produced to provide amino acids, minerals and vitamins for human nutrition. When GHG emissions from meat and milk production are expressed per unit first-limiting amino acid rather than per unit total protein such production is seen in a new light (Moughan, 2021). Recent modelling using Linear Programming demonstrates, that given current price relativities, that animal-based products are needed to provide least-cost diets (diets that meet all nutrient requirements at the lowest cost) (Macdiarmid et al., 2012; Chungchunlam et al., 2020). It would appear that the cost of some animal products would need to increase greatly, before they would no longer be found in a least-cost diet. Sustainable diets must be affordable. The issue is nuanced, and entrenched "blanket" positions should be avoided. The development of new farming systems (eg insect, algae, single-cell food production, and in vitro meat production and biotech foods) should be encouraged and their integration into the more traditional land-based systems carefully assessed.

The expansion of aqua-culture will likely occur in the future, and STI is needed to improve the genetics of farmed fish and crustaceans, as well as developing systems that mitigate against eutrophication. A key target in developing more sustainable farming systems will be the reduction of food/nutrient wastage, and here food science STI has a vital role to play. The DELTA Model (https://sustainablenutritioninitiative.com/) has recently been developed and calculates nutrient availability to consumers from differing global food production scenarios. Early findings from the model indicate that global food production currently supplies sufficient macro- and micronutrients to nourish the global population if equally distributed, with the exception of calcium and Vitamin E. These nutrients appear to be undersupplied by at least 30%. Total removal of food waste from the model although helpful does not solve these insufficiencies. Nutrient loss due to food waste is not constant across all nutrients: relatively little calcium and vitamin E is wasted, whereas waste of carbohydrates and protein is high. Further, while the current food system would provide sufficient energy and protein for the forecast 2030 global population of 8.6 billion, it would fail in supplying several micronutrients (calcium, iron, potassium, zinc, riboflavin and vitamins A, B12 and E).

Addressing food-energy-water nexus and other natural resources

The AASSA working group addressed land use for food production in light of competing interests (eg urbanisation, textiles, biofuel, ecological restoration, recreational use). An evidence based and total systems based (accounting for the principles of re-cycling and circular agriculture) approach is urged to ensure planning to make optimal use of limited land, water and other resources.

Supporting and using outputs from fundamental research

Although the role of applied science, technology and extension is likely to be pivotal in solving key issues, the potential for 'game-changing' new discoveries arising from fundamental science should not be overlooked. Recent-past discoveries in molecular biology, IT, cell biology serve as shining examples of the power of 'unfettered' scientific endeavour. Strong programmes in fundamental science are encouraged. At the same time, well-targeted applied research programmes will need to place less emphasis on increasing plant and animal production per se, and will need to seek to optimise agricultural outputs in face of multiple externalities. Cross-disciplinary systems research, bioecological farming, and farm management science will all be important.

Consequences of COVID-19

The COVID-19 pandemic has highlighted the vulnerability of global food systems (eg rising unemployment and loss of purchasing power, loss of seasonal labour, disruption of food processing and food distribution). Global food systems need to be resilient (International Food Policy Research Institute (IFPRI), 2020b; Di Marco et al., 2020). The pandemic further highlights the role of good nutrition and healthy diets in supporting the immune system (Calder, 2020).

Strengthening Policy for Research and its Uptake

Planning for and securing FNS in Asia will require dedicated and bold commitment from politicians and policy makers, while scientists in the region have the responsibility to provide robust peer-reviewed scientific knowledge, to allow evidence-based decision making.

The AASSA Working Group urged the establishment of a trans-national funding mechanism in the region (similar to that in the European Union), focussing on inter-disciplinary FNS STI. Considering the often considerable lag time in research between investment and adoption, it is imperative that governments in the region not only maintain support for R&D, education and extension related to FNS, but also greatly increase, as a matter of urgency, the overall level of funding. Funding in agriculture and related disciplines has declined over recent decades (AASSA, 2018). There needs to be a considerable resurgence in agri-food R&D, extension and education, and such an emphasis needs to be more cross-disciplinary and systems oriented than in the past. Several areas of STI are seen as universally important for the region (see earlier section), and it is strongly recommended that a cooperative regional approach be taken, to form well-resourced regional centres of excellence that focus on key areas of opportunity.

The importance of formulating an evidence-based 'blueprint' for FNS R&D in the region is stressed. If progress is to be maximised funding needs to be carefully targeted. Systems research needs to be applied, early on, to identify critical impediments that currently affect the region's ability to increase food production sustainably and to ensure a diversity of high-quality foods reaching the consumer. The knowledge generated must be communicated rapidly, and shared freely and extensively. In addition to a ramping up of R&D effort, funding should also be allocated to education at all levels and to "on-farm" and "in-factory" extension. Over and above regional cooperative STI initiatives, there is much opportunity for accelerated collaboration through targeted global alliances, and national/regional policies should incentivise this. A lesson from COVID-19, is that with restricted travel, the necessary IT infrastructure needs to be in place and available to all to allow unimpeded collaboration across boundaries and borders. Networking will be paramount.

Ongoing support for international STI programmes such as CGIAR, IFPRI and ICARDA is urged, as is the incentivisation of public-private partnerships (Fanzo et al., 2020b).

In formulating an STI strategy for the region, the potential power of fundamental science should not be ignored. Discoveries, often arising from fundamental science, have the capacity to lead to step-changes in agricultural productivity. Examples of emerging disruptive technologies are found in bio-based manufacturing to produce fuels, chemicals and materials through advanced, efficient and environmentally friendly approaches. Synthetic approaches to producing animal-free meat and milk have attracted much attention. Such products may have advantages in cost of production, ethical acceptance and sustainability, but consumer acceptance is yet to be tested.

Agricultural and rural development were priorities for foreign aid and international development banks before the mid-1980s, but investment in this area has declined in subsequent years. Agriculture and food have been off the global development agenda and this must be reversed.

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This report presents an update and summarised version of the report 'Opportunities and challenges for research on food and nutrition security and agriculture in Asia', available at https://www.interacademies.org/publication/opportunities-and-challenges-research-food-and-nutrition-security-and-agriculture-asia.

The Role of Science, Technology, and Innovation for Transforming Food Systems in Europe

by Claudia Canales Holzeis and Robin Fears

The UN FSS provides an important stimulus to develop new momentum to tackle shared challenges for achieving food and nutrition security. For this Brief, EASAC provides an assessment of the science to update our previous contribution to the IAP global project. European farming systems are diverse and food has traditionally played a central role in the shaping of individual and cultural identities. In this Brief taking a food systems approach, we examine European issues for the interrelationships between agriculture, environmental sustainability, nutrition and health, considering all steps in the food value chain from growing through to consumption and recycling.

There are multiple policy objectives and instruments to coordinate but, although the challenges are unprecedented, so too are the scientific opportunities. A wide range of issues are covered, including those for: agro-ecology and the implications for ecosystem assessment, other new production systems, linking soil structure and health both with environmental sustainability and novel products of the bioeconomy, and microbiomics. However, capitalising on scientific advances is not sufficient, there must also be flexibility in regulatory systems to encourage innovation. EASAC recommends that it is the products of new technologies and their use, rather than the technology itself, that should be evaluated according to evidence-based regulatory frameworks.

There are major opportunities for developing climate-resilient food systems while, at the same time, reducing the contribution that agriculture makes to climate change, and the implications for food policy. The COVID-19 pandemic has also brought significant adverse pressures on food systems but planning for a sustainable economic recovery after the pandemic can facilitate efforts to make food systems more resilient, nutritious and environmentally sustainable.

We make three core recommendations for ambitious action to generate and use research:

1. Promoting transdisciplinary research to fill present knowledge gaps.
2. Continuing to strengthen the research enterprise in the EU: this requires public engagement to build trust, developing better linkages between public and private sector research objectives, and recognising that EU scientists have crucial roles to play in building global critical mass in food systems science.
3. It is very timely to reaffirm the use of science to inform innovation, policy and practice. In particular for the EU, the Farm-to-Fork policy has important objectives but must be fully informed by the scientific evidence, well aligned with objectives for the Common Agricultural Policy and with the biodiversity, circular economy and bioeconomy strategies, and transparent in communicating the consequences both for the domestic consumer and for the rest of the world.

Introduction: the transformation of European food systems

Combating malnutrition in all its forms – undernutrition, micronutrient deficiencies, overweight and obesity - is a problem faced by all countries. Recent data confirm that undernutrition and food insecurity are present in vulnerable groups in Europe (Loopstra, 2018; Pollard and Booth, 2019; Leij-Halfwerk et al., 2019) at the same time as an increasing public health burden of obesity (Pineda et al., 2018; Krzysztoszek et al., 2018). There is still much to be done to ensure access to safe and nutritious food for all (UN FSS Action Track 1[III]). Europe has a rich diversity in food cultures in close proximity to each other, and this diversity is mirrored in the structure of the EU farming sector: very small farms (< 2 hectares) make up nearly half of the agricultural holdings, while very large farms (> 100 hectares) make up just 3% of the total but cultivate half the farmland (Kania

III https://www.un.org/en/food-systems-summit/action-tracks.

et al., 2014). Small farms themselves differ widely and include high value and specialised production systems (Guiomar et al, 2018). Food has also traditionally played a central role in the EU in the shaping of individual and collective identities (Anderson et al, 2017), and it is also central in current discourses on economic, social and environmental justice and of cultural recognition (e.g. Coolsaet, 2016; Šūmane et al, 2018). There is large variation in food and nutrient intakes across Europe, between and within countries (Martens et al., 2019).

In 2017, EASAC published a report on food and nutrition security and agriculture in Europe as part of the InterAcademies Partnership (IAP) global project. That report followed an integrative food system approach to cover inter-related issues for resource efficiency, environmental sustainability, resilience and the public health agenda while also addressing opportunities for local-global connectiveness and for the bioeconomy. EASAC emphasised that an earlier food security emphasis on agricultural production now has to be replaced by the food systems approach to encompass all of the steps in the food value chain to deliver accessible and affordable food for all, from growing through to processing, trading, consuming and disposing of, or recycling, waste. Food systems must include both supply-side and demand-side considerations for sustainability. Yearly food losses in the EU have been estimated at about 15% of the emissions of the entire food supply chain (Scherhaufer et al., 2018). An increase in agricultural productivity would likely increase the environmental footprint without necessarily delivering healthy and nutritious diets accessible to all, unless embedded in a profound transformation of food systems (Benton and Bailey, 2019).

One issue increasing in importance is the role of public procurement in the demand for sustainable, healthy food (Sonnichsen et al., 2020, WHO, 2021): provision of sustainable, healthy diets in hospitals and other public services can help to change consumer behaviour in the longer-term (EASAC and FEAM, 2021). European Union interest in the sustainability of the food systems approach is increasing (e.g. SAPEA, 2020) and the recent Farm-to-Fork policy initiative covers all the food chain, together with protection of the environment.

Much of the EASAC 2017 report focused on scientific advances in agriculture but there was also significant attention to food science and technology, e.g. for food safety and food processing to reduce food losses, extend distribution and seasonal availability, and for food fortification. The comprehensive recent work of the International Union of Food Science and Technology[IV], based partly on evidence presented by IAP and its regional work streams, reviewed scientific opportunities relating to diverse and sustainable primary production; sustainable process and system engineering; eliminating waste in production, distribution and consumption; and traceability and product safety (see also Lillford and Hermansson, 2020). An additional issue, brought into prominence by the COVID-19 pandemic, is the potential of the improved food value chain to address poverty by increasing entrepreneurial activity and other employment (an issue thatshould be highlighted in UN FSS Action Track 4, Advance equitable livelihoods).

Transdisciplinary policy making and governance are required to make food systems more nutrition-sensitive. Food and nutrition security and food sustainability must now be considered as part of formulating European dietary guidelines. Some of the research priorities are described subsequently but there is also need of a better definition of what a sustainable diet is and how it can be measured, so that these metrics form part of national surveys and inform policies and interventions to educate consumers on sustainable behaviours and diets.

Innovation is central for delivering the required transformation of food systems, and must be based on transdisciplinary science, new financing and business models, and policy development. This topic has received renewed attention recently. For example, Herrero et al. (2020) developed an inventory of innovations organised according to their position in the value chain (i.e. production, processing, packaging, distribution, consumption and waste) and their 'readiness score': from basic research all the way to proven implementation under real-world conditions. The dissemination and uptake of these innovations should be considered a priority, and research is urgently needed on how to make options available in current food systems with minimal disruption.

In this EASAC brief the following sections update selected priorities from the EASAC 2017

IV Global challenges for food science and technology, 2019, https://iufost.org/global-challenges-and-critical-needs-2/).

report in order to demonstrate how science, technology and innovation can provide major contributions to the UN FSS Action Tracks. There are multiple implications for EU policy, summarised in Figure 1.

Agriculture-environment nexus and agroecology in Europe

Linkage of food systems to sustainable development objectives is a core part of the integrated transformations required to attain the Sustainable Development Goals (SDGs, see GSDR 2019; Sachs et al., 2019; EASAC, 2020a). Concomitantly, there is great potential for new business opportunities and economic value (WEF, 2020), but also need to understand co-benefits and trade-offs for coupling nutritional and environmental objectives for SDGs (McElwee et al., 2020) and these also need to be taken into account in UN FSS Action tracks 2 (Shift to sustainable consumption patterns) and 3 (Boost nature-positive production).

The concept of regenerative agriculture (Newton et al., 2020; Schreefel et al., 2020) embraces farming principles and practices that enhance biodiversity and ecosystem services and increase carbon capture and storage, helping to tackle climate change and improve agricultural resilience and yield. This can be viewed as a core feature of the EU's Farm-to-Fork strategy but the scientific basis needs to be clarified in order to improve farming systems (Davies et al., 2020). Agroecology is an important part of regenerative agriculture innovation (HLPE, 2019): scientific advances here will also help to clarify links between human and livestock health and their dependencies on the environment.

Assessing the relative contribution of different production models to sustainably deliver healthy and nutritious diets and provide important ecosystems services is an important research priority. For example, using life cycle assessments (LCAs) it was estimated that a complete switch to organic cultivation in England and Wales lowers production emissions but also decreases yields, and the increased reliance on land use elsewhere to make up for the shortfall would result in higher emissions overall (Smith et al., 2019). However, organic agriculture can decrease the reliance on chemical inputs, improve soil carbon sequestration and soil quality, reduce the contamination of water bodies and increase biodiversity. LCAs do not accurately reflect these benefits because of their focus on the product, whereas ecosystem services from agricultural systems are not duly considered. Deploying an integrated approach requires research to quantify the economic value of ecosystems (Dasgupta, 2021), as part of the improvement and standardisation of methodologies to assess and compare the sustainability of food systems. In addition, estimates of the levels of food production required to fulfil demand often fail to take into consideration the effects of a switch to more sustainable diets, lowered consumption patterns, and reduction of food waste.

Research for improving the environmental assessments of production systems should include clarification of additional indicators, such as for land and soil degradation and loss of biodiversity; broadening the scope to include the provision of ecosystem services; and improving the assessment of indirect effects within a comprehensive food systems perspective, as opposed to a narrow focus on yield (van der Werf et al., 2020). Organic agriculture should also embrace innovation to improve its performance (Seufert et al., 2019; Clark, 2020) and may require multiple policy interventions to realise its potential for food systems sustainability (Eyhorn et al., 2019). Communicating effectively to consumers the relative environmental footprints of different foods must also be a priority (Potter and Röös, 2021).

Diverse farming systems depend on soil structure and health. In discussing how to manage competition for land use and other resources, EASAC (2017) highlighted the critical role of soil, particularly with respect to its biological functions. More recent EASAC assessment (2018) further emphasised the multiple roles of soil sustainability, and implications for its management to inform policy development, relatively neglected recently in the EU. This neglect needs to be corrected. Among soil's biological functions EASAC (2017) discussed emerging knowledge about the contribution of soil microbiomics (bacteria and fungi) to sustainable agriculture, e.g. in strengthening of root systems and carbon sequestration. There is another link to the bioeconomy: the soil microbiome can be a resource for generating novel antibiotics and other high-value chemicals. Rapid progress continues, to ascertain the linkages between microbial diversity and ecosystem functions, including plant health under climate change; in particular the role of soil microbial taxa in biogeochemical cycling, plant growth and carbon sequestration (Dubey et al., 2019; Wei et al., 2019).

There are continuing opportunities to link food systems and environmental objectives with bioeconomy policy: impetus and coordination has been imparted to the European

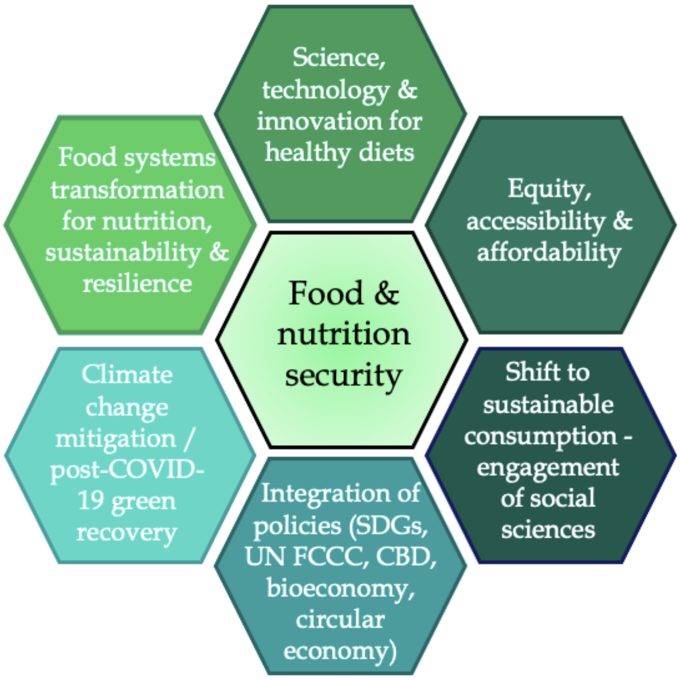

Figure 1: Matrix of European policy objectives for food and nutrition security. Links with international policy development are particularly relevant in 2021 because of the UN FSS and also COP26 of the UN FCCC (Framework Convention on Climate Change) and COP15 of the UN CBD (Convention on Biological Diversity).

Bioeconomy Strategy by recent introduction of an EU-wide monitoring system[V] to track the balancing of bioeconomy contributions to food and other outputs, in order to reduce environmental pressures. Systematic review of the literature suggests the need to prioritise biomass strategies to increase food production over those for animal feed or biofuels (Haines, 2021). Scientific advances are bringing new opportunities to drive the bioeconomy of future foods (such as mycoproteins, algal feedstocks, cultured meat; Fanzo *et al.*, 2020; Haines, 2021).

Delivering sustainable and healthy diets under climate change

Climate change is already affecting the yield and quality of crops with the potential for adverse consequences in terms of malnutrition (undernutrition, micronutrient deficiency, obesity, EASAC, 2017). Systematic reviews of the literature have documented declines in yield of starchy staple crops (Wang et al., 2018b) and in yield and nutritional quality of vegetables and legumes (Scheelbeek et al., 2018) and fruits, nuts and seeds (Alae-Carew et al., 2020). Developing climate-resilient food systems should be a core part of UN FSS Action Track 5 (Build resilience to vulnerabilities, shocks and stress).

It is important to evaluate how the agricultural sector can adapt to climate change and, at the same time, reduce its own contribution to Greenhouse Gas (GHG) emissions. Agriculture currently accounts for about 30% of total GHG emissions if including land conversion and production-linked direct environmental costs (EASAC, 2019). A key objective, therefore, for the UN FSS when developing environment-health-climate change policies is to reduce the triple burden of malnutrition at the same time as reducing the contribution that food systems make to climate change and other environmental changes. The accumulating evidence indicates that 1.5° and 2° C targets cannot be attained without rapid and ambitious changes to food systems (Clark et al., 2020). A combination of measures is necessary to reduce GHG emissions from agriculture, including improved agronomic practices, reducing waste, and increasing sustainable consumption patterns. The evidence base indicates significant health benefits from reducing red meat consumption (where that is excessive) and increasing vegetables, fruits, nuts and seeds in diets (EASAC, 2019; Willett et al., 2020). The impact of changes to dietary guidelines on micronutrient intakes must be considered, especially for vulnerable groups. A recent systematic review of environmental footprints and health effects of "sustainable diets" (Jarmul et al., 2020), concluded that although co-benefits are not universal and some trade-offs are likely, when carefully-designed and adapted to circumstances, diets can play a pivotal role in climate change mitigation, sustainable food systems and future population health. Unfortunately, in proposing recommendations for policy solutions, issues for accessibility and affordability of proposed healthy and sustainable diets are often overlooked (Hirvonen et al., 2020).

Policy implications for the promotion of sustainable food systems that reward good management practices include the introduction of sustainable stewardship, food labelling and certification schemes. Current food policy in many countries concentrates more on how to protect consumer health

V EU Bioeconomy Monitoring System, 2020, https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en.

from contaminated food than the degree to which the State should use health and environmental considerations to regulate the supply of foodstuffs (Godfray et al., 2018). Resolving this role of the State has significant implications for rebalancing consumption by introducing incentives/disincentives for carbon and biodiversity costs of populations at risk of over-consumption, while protecting vulnerable groups. At the same time, governments must consider how best to measure and monitor policy changes for their impact on food production, consumption and health.

Responding to COVID-19

The ongoing COVID-19 pandemic has affected all components of the food system. Long-term implications are hard to predict as they will depend on the length and severity of the pandemic. The effects may be also compounded by shocks to production (such as drought and the interruption of seasonal labour supply for planting and harvesting), and by factors influencing the distribution, access and affordability of food (e.g. disruptions to global food trade and food price speculations; Moran et al., 2020). To date, global supply chains continue to function in spite of isolation policies (Galanakis, 2020; Moran et al., 2020), although production problems that resulted in an increase in the price of fresh and perishable products have also been reported (Coluccia et al., 2021). In Europe there has been an increase in food wastage, partly as a result of the shutdown of restaurants, schools and other community facilities. The pandemic has affected the ability to access sufficient and health food by vulnerable groups of the population due to rising unemployment and enforced self-isolation, in particular for families with young children, and is exacerbating diet-related health inequalities (Power et al., 2020). Consumption related challenges reported during lockdowns include a small increase in the intake of calories and a decrease in the intake of vitamins, minerals and plant-based protein and fatty acids, in particular by the elderly as a group (Batlle-Bayer et al., 2020; IUFoST, 2020). Combined with reduced physical exercise during lockdown these dietary changes may increase the incidence of obesity and related NCDs. Hoarding and panic buying during pandemics, also reported, could distort the food supply chain and need to be better managed (IUFoST, 2020; O'Connell et al., 2020).

Planning for a sustainable economic recovery after the pandemic provides a window of opportunity to make food systems more resilient, nutritious and environmentally sustainable, avoiding a return to business-as-usual. (EASAC, 2020b; Benton, 2020; IUFoST, 2020; Rowan and Galanakis, 2020; Sarkis et al., 2020). Because the pandemic exposed vulnerability of the overreliance on just-in-time and lean delivery systems, globalised food production and distribution systems based on complex value chains should be re-examined not only in terms of economic efficiency but also for their environmental sustainability and climate change mitigation potential. Opportunities for the increased localisation of production systems should be explored. Research priorities also include the development of food safety measures and bioanalytical protocols for food and environmental safety along the food chain; and the development of nutritional foods to promote immune function, which may include foods for medical use by the elderly population as well as other vulnerable groups. Further areas for innovation to capitalise on scientific opportunities comprise digitisation and the implementation of smarter logistics systems, including reverse logistics for secondary materials and waste products (IUFoST 2020; Rizou et al., 2020; Rowan et al., 2020; Sarkis et al., 2020). The generation of robust baseline data on malnutrition levels in the EU Member States remains an important knowledge gap, in particular for vulnerable sectors of the population (EASAC, 2017).

New breeding techniques: a case study in science, technology and innovation

Improved breeding of plants and animals for agricultural production is a key component of an integrated transformation of food systems to deliver healthy and nutritious diets sustainably in the face of climate change. For plants, key target traits for improvement include increased tolerance to drought (including soil water use efficiency), heat, and salinity, with a focus on the development of multiple traits; improved use of soil nutrients (nitrogen, phosphorous and essential elements) to reduce dependency on fertilisers; pest and disease resistance; and healthier nutrient composition (EASAC, 2017; 2020c). Animal breeding priorities comprise animal health (disease resistance and stress tolerance, in particular heat); and nutrition, including strategies to mitigate enteric gut methane emissions (Pryce et al., 2020). Achieving these objectives will require the use of the full tool box of breeding technologies available, from conventional breeding assisted by advances in genetics and genomics, through to the use of a set of technologies collectively referred to as new breeding techniques (NBTs) and, in particular, genome editing.

Recent advances using genome editing include the development of varieties with improved nutritional content, such as high protein wheat with increased grain weight, and more nutritious potatoes (Hameed et al., 2018; Zhang et al., 2018, 2020). In wheat, gene editing has also been used to derive low-gluten transgene-free plants (Sánchez-León et al., 2018). Gene editing allows developing crop varieties with multiple resistances to biotic and abiotic stresses (e.g., in tomato: Saikia et al., 2020). Looking ahead, research priorities include the (re)domestication of high-nutrient stress-tolerant crops by targeting known domestication genes in established crops (e.g. for the cultivation of quinoa in Europe; López-Marqués et al., 2020; and see also van Tassel et al., 2020; Zhang et al., 2020), and for the development of perennial grain crops to maximise sustained crop yields (DeHann et al., 2020).

Crops produced by genome editing techniques, including those with no foreign DNA, are regulated differently in different countries (Schmidt et al., 2020), with Europe holding the most restrictive regulatory regime. In 2018, the European Union Court of Justice ruled that crops produced by gene editing technologies are to be subjected to the same regulations as GM crops (Directive 2001/18/EC). The focus of this regulation is the process by which a crop is developed, not the breeding product, and as a result crop varieties which are equivalent from a scientific perspective but were developed by different methods will be regulated differently (Jansson, 2018). The legislation's far-reaching consequences, include the stifling of innovation, since the cost of pre-market evaluations will deter investment in the technology, in particular in the public sector and by small and medium enterprises (SMEs; Ricroch, 2020; Jorasch, 2020). Around 40% of the SMEs and 33% of the large companies stopped or reduced their gene editing-related R&D activities after the 2018 ruling (Jorasch, 2020). The EU is also lagging behind in terms of generating innovation: while the United States and China have filed 872 and 858 patents for applications for gene editing applications, respectively, EU countries together have filed only 194 (Martin-Laffon et al., 2019). There has also been a very striking reduction in the number of EU countries carrying out field trials of crops improved by either GM or gene editing (Ricroch, 2020). In addition, the impossibility of distinguishing between edited and naturally derived varieties makes the law unenforceable, especially if the varieties are considered legal elsewhere (Martin-Laffon et al., 2019; Schmidt et al., 2020; Zhang et al., 2020).

EASAC advised (EASAC, 2020) that it is the products of new technologies and their use, rather than the technology itself, that should be evaluated according to the scientific evidence base, and that the legal framework should be revised. The potential costs of not using a new technology, or being slow in adoption must be acknowledged as there is no time to lose in resolving the problems for food and nutrition security.

Strengthening research and its uptake into policy and practice

The purpose of this Brief has been to address three questions: How can scientific advances help to fill knowledge gaps in delivering food and nutrition security? What does Europe need to build its research capabilities and help build global scientific capacity and partnerships? How best can science-based evidence be used to inform innovation, policy development and practice? Our recommendations are as follows.

- **Filling knowledge gaps with new research**
  In the previous sections, we have exemplified how new research is of unequivocal value in addressing societal challenges. In addition to these examples, and referring back to other scientific priorities in EASAC, 2017, there have been recent advances in big data handling, robotics, artificial intelligence and mobile communications for precision agriculture (Klerkx and Rose, 2020; El-Gayar et al., 2020). There have also been substantial advances in the science of human gut microbiomics and linkages to diet and health. For example, methodological studies are rapidly clarifying characteristics of a healthy microbiome (Eisenstein, 2020) and intervention studies have demonstrated the health value of a Mediterranean diet in older cohorts in different European countries, explained

in terms of gut microbiome alterations (Ghosh et al., 2020). Advances in social sciences research are increasingly important to understand determinants of inequity in food systems, mechanisms for empowerment of marginalised groups and models for entrepreneurial activity (Fanzo et al., 2020). Social sciences research is also helpful for evaluating specific instruments for promotion of sustainable food in EU policy, e.g. taxation schemes, consumer cooperatives, labelling and governance initiatives (Marsden et al., 2018; SAPEA, 2020).

- **Building the research enterprise**
Europe has mature systems for research funding at national and EU level (EASAC, 2017). Nonetheless, it is essential for the scientific community to continue making the case for investment in research, including fundamental science, and to recognise the value of involving other stakeholders in the design and conduct of research (SAPEA, 2020). Greater inclusivity depends in part on building public confidence in science and shaping public understanding of the challenges to food and nutrition security in a changing public landscape often characterised by less deference to authority and scientific experts (Fears et al., 2020). Strengthening research capabilities in Europe also depends on understanding the impact from the progressive loss of key skills in the EU (e.g. in plant sciences), and on reversing those losses while also developing new skills needed by the next generation of researchers (e.g. in transdisciplinary thinking). The EU also has an important role in developing global critical mass in research, e.g. by research partnerships, sharing data and infrastructure, and contributing to tackling those problems that can only be addressed at the global scale. The European Commission recently launched an important initiative to assess the need for an international platform for food systems science[VI].

- **Translating research outputs**
Ensuring the robustness, legitimacy and relevance of scientific evidence is vital if its impacts on innovation, policy and practice are to be realised. Overcoming obstacles in translation also depends on public confidence in science, on integrating outputs from across diverse disciplines (evidence synthesis for sustainability, Anon, 2020), taking account of new models (e.g. for open innovation) and of trade-offs between different goals, e.g. for nutrition and environment (Fears et al., 2019). Academies of science are well-placed to help lead the scientific community at the science-policy interfaces. The EU already has a relatively mature science-policy interface in place, whose operational characteristics may serve as a model for other regions (Fears et al., 2019) and, currently, there is active scientific engagement in a diverse range of public policies in development, including Farm-to-Fork (F2F), Common Agricultural Policy and Biodiversity strategy, bioeconomy, circular economy and the European Green Deal. The F2F strategy has important and comprehensive objectives but it remains important to clarify and resolve governance challenges, including the tangible links to Member State action (Schebesta and Candell, 2020). There is also ambiguity in defining food sustainability and, currently, a mismatch between F2F and the Common Agricultural Policy that must be resolved by developing compatible legal instruments and ensuring better coordination between the relevant Directorate-Generals (for health and agriculture). F2F highlights several controversies, e.g. on the objectives for food pack labelling, targets for pesticide use in farming, and nature-based farming solutions, all of which require a stronger evidence base. Moreover, modelling different scenarios for adopting the proposed F2F targets (Beckman et al., 2020) finds reductions in EU agricultural production and diminished competitiveness in both domestic and export markets. Modelling also predicted consequences for the rest of the world, driving up food prices and negatively affecting consumer budgets. While the F2F strategy is rather inward oriented and has given little explicit attention to external effects in the rest of the world, depending on how incentives/disincentives are applied in the EU, there is risk of pushing consumers towards import of food produced less sustainably than in the EU. Therefore, there must be much more assessment of the potential consequences of the F2F proposals within the broad

VI https://ec.europa.eu/info/news/new-high-level-expert-group-assess-need-international-platform-food-systems-science-2021-feb-17_en.

context of food systems transformation.

The EU can also teach a cautionary lesson on the obstacles created by inflexible regulation delaying or impeding the translation of research outputs into innovation and practice. In the case study discussed previously, the EU GMO regulatory framework was found to be inflexible, disproportionate, not based on current scientific evidence and not fit for purpose. Urgent reform of the regulation of new plant (and animal) breeding techniques is essential for agricultural innovation to realise its potential in achieving SDG targets, for the EU to maintain its international competitiveness and to obtain value from its public investment in research (EASAC, 2020c). The current obstacles have implications beyond the EU: EU policy decisions have consequences for those LMICs who look to the EU for scientific leadership or as a market for their innovative exports.

In conclusion, the use of science and technology to transform food systems for health, nutrition, sustainable agriculture and the environment depends on progress across a transdisciplinary research agenda but also on facilitating the use of science by stakeholders, such as farmers, manufacturers, regulators and consumers, as well as policy makers. It is time to be more ambitious for identifying, investing in, and using, the scientific opportunities. Academies of science stand ready to play their part in catalysing the necessary actions for food systems in transition, and at the science-policy interface.

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The Role of Science, Technology and Innovation for Transforming Food Systems in Latin America and the Caribbean

by Elizabeth Hodson de Jaramillo, Eduardo J. Trigo and Rosario Campos

Food systems (FS) incorporate nutrition, health, resource use, biodiversity, transformation, jobs and livelihoods that ideally should be under the concept of the SDGs. The InterAcademy Partnership (IAP) published since 2018 regional and global reports on scientific opportunities and challenges for research on food and nutrition security and agriculture.

The Americas report outlined the crucial role of the region as the world's largest net exporter of agricultural products and recognize the circular economy and the bioeconomy as two strategic areas for FS transformation to improve productivity and sustainable use of biological resources and to reduce waste. The region makes vital contributions to several development objectives, including growth and trade promotion, poverty reduction, food and nutrition security, ecosystem services and climate resilience. There is a substantial diversity in STI capacities among the countries, with many having to confront significant restrictions, particularly with respect to financial and human resources.

Nevertheless, significant developments have been made in some countries in biotechnology agricultural applications, conservation and regenerative agriculture and sustainable livestock production systems, as well as young entrepreneurships developing start-ups with impact in the regional bioeconomy. Considering this dichotomy should be an essential component of any strategy to confront the climate change crisis, and the aftermath of the COVID-19 pandemic, that are threatening food supply, nutrition, health and sustainability. The transformation of FS in Latin America and the Caribbean (LAC) with more precision and efficiency requires comprehensive, participatory and inclusive approaches that make full use of current and future scientific advances, including biotechnologies and digital technologies.

Those advances are already transforming global agriculture where one is producing more with less, increasing efficiency, and reducing residues. Integration of STI developments and investment opportunities with national and regional policy making is essential, as well as communicating its potential to the public. Specific actions for LAC include: (a) use the great agrobiodiversity of LAC to diversify the FS, thereby increasing nutritional content and climate change resilience and new bioproducts; (b) enable and promote the use of digital technologies in the food value chain: and (c) use beneficial soil microorganisms and the microbiome for sustainable increases in productivity.

Introduction

The transformation of Food Systems (FS) can produce huge benefits for health, food security and nutrition, sustainable agriculture and nature. Central to this discussion is the understanding that food systems are demand-led (IFPRI, 2020) and represent the full agri-value chain, which includes growing, harvesting, processing, transporting, marketing, consumption, distribution and disposal of food and food-related items, plus the inputs needed and outputs produced at each of these steps. They integrate nutrition, health, resource use, biodiversity, transformation, jobs and livelihoods that ideally should be under the concept of the SDGs. As an economic complex, they provide close to 1.3 billion jobs and for the livelihoods of over 3.2 billion people around the world. In this sense, transforming FS becomes a key, if not the main issue for making real progress towards all 17 SDGs. by 2030 (UN, 2020). Science, technology and innovation (STI) offer a wide and expanding range of opportunities for making real progress towards these objectives. This paper looks at the involved issues with a focus on Latin America and the Caribbean (LAC).

IAP and IANAS reports "Opportunities for future research and innovation on food and nutrition security and agriculture"

The IAP report (2018) emphasizes the urgent need to mobilize financial and human resources to promote the shift towards more efficient and sustainable food systems, an effort which demands profound changes in the way that food is produced, consumed and the resulting waste disposed. Collaboration between the natural and social sciences is required to find sustainable solutions to food systems, as well as an efficient international science advisory mechanism. There is a wide range of scientific opportunities, and making the most of them is a wise public policy decision. Furthermore. all stakeholders must be included along the value chain in an integrated way.

The reports highlight that the transformation of FS requires a coordinated global approach to promote application of research to innovation, connections among disciplines and sectors including cooperation with policies, and enhancement of scientific infrastructure with collaboration between countries, and recognize the circular economy and the bioeconomy as two strategic areas for FS transformation (Lachman et al, 2020; IANAS, 2018). Their main recommendations include: a) Promote substantive changes towards climate-smart food systems. b) Develop incentives for consumers to modify and to improve their diets. c) Reduce food waste. d) Develop innovative foods. e) Increase cooperation between life sciences and social sciences as well as policy research on food, nutrition and agriculture to translate advances into applied innovation. f) Foster international cooperation through advisory mechanisms (IANAS, 2018; IAP, 2018).

Food and nutrition aspects, healthy diets

In relation to nutritional aspects, the Americas present a picture of sharp contrast. The region has an exceptional abundance of natural resources, considerable wealth in agrobiodiversity, arable land and availability of water. These constitute major advantages for the future, and make the Americas the largest net food exporter in the world, and the largest producer of ecosystem services. The region makes vital contributions to several development objectives, including growth and trade promotion, poverty reduction, food and nutrition security, ecosystem services and climate resilience. Moreover, aquaculture is emerging as a major industry in a number of countries such as Canada, Chile, Mexico, Peru, Argentina and Ecuador (Morris et al., 2020; IANAS, 2018). However, malnutrition, food insecurity, obesity and other related diseases coexist to a greater or lesser degree throughout the region. There has been a rise in hunger, with the number of undernourished people increasing by 9 million between 2015 and 2019. Food insecurity in LAC went from 22.9% in 2014 to 31.7% in 2019, due to a sharp increase in South America, and over 100 million people cannot afford a healthy diet (FAO, 2020a).

For the transformation to sustainable and healthy diets, the research agenda related to food choices must explore alternative ways of influencing consumer behaviour (IAP, 2018). Among the factors that define healthy diets are availability, affordability, and social and cultural issues. LAC's great agrobiodiversity, and the potential of nutritious, but underutilized or neglected, indigenous crops represent a great opportunity for transformation towards sustainable systems, more balanced diets, and increased resource efficiency and resilience. High diversity in aquaculture in LAC provides wider opportunities for balanced diets (Hodson de Jaramillo et al., 2019).

Science and technology and food systems transformation

STI is essential to address the multidimensional nature of food security and food systems. New and emerging technologies in the field of the biological sciences, information and communication, data sciences, artificial intelligence, and associated digital applications are significantly improving the production and productivity of crop and livestock and the quality of food and biomass. Advances in breeding provide means of developing disease tolerant and environmentally friendly varieties of plants and animals. STI also contributes to improved resource use and waste reduction, as well as increasing the overall economic organization and competitiveness of FS. (Basso & Antle, 2020; Saiz-Rubio & Rovira-Más, 2020; ECLAC, et al, 2019; HLPE, 2019; Trigo & Elverdin, 2019; Rose & Chilvers, 2018). In turn, the emerging concept of the circular bioeconomy—keeping renewable components and materials in the system during successive processes while protecting ecosystems using STI—makes it possible to improve productivity and sustainable use of biological resources and to reduce waste. This approach allows the development of new bioproducts with high value-added such as nutraceuticals, biofortified foods, bio-inputs for agriculture, bioenergy and biomaterials for the cosmetic, pharmaceutical, chemical and other industries (Brandao et al., 2021). It generates a range of new services and attaches greater value to biodiversity, for example, integrated pest management based on biological pesticides and fertilizers. It contributes to increase the efficiency of converting biological resource for food, feed, soil health, and other uses by improving biorefinery processes (Trigo et al, 2021, Lachman et al, 2020; ECLAC et al, 2019).

The current STI scenarios for FS transformation offer very concrete opportunities to contribute to the SDGs particularly to: SDG 1 (Reduce poverty), SDG 2 (Reduce hunger), 3 (Good health and well-being), 6 (Clean water and sanitation), 7 (Affordable and clean energy), 8 (Decent work and economic growth), 9 (Industry, innovation and infrastructure), 12, (Responsible production and consumption) , 13 (Climate action), and 15 (Life on land).

These STI scenarios play a key role in the provision of sustainable agricultural development, climate resilient, producing healthy nutritious foods, and guaranteeing global food security. New developments in agricultural technology will play a leading role in moving our food systems towards more sustainable schemes (Trigo & Elverdin, 2019). Biotechnology has evolved more efficient and faster ways of doing research in breeding programs in agriculture which, combined with digital technologies, potentiate the agricultural advances to produce more with less, which in turn are being proactively reflected throughout the food system (Virginia Tech, 2020).

Global agriculture is undergoing major transformations through the convergence of digital, biological and engineering technologies (ECLAC, 2021; Basso and Antle, 2020; Santos Valle & Kienzle, 2020; Rose & Chilvers, 2018), to optimize agricultural production processes and input utilization in the so-called Agriculture 4.0. The adoption of the new technological strategies must be prudent and based on transparent, inclusive and participatory social processes, adapted to the local conditions, capacities and cultures (ECLAC et al., 2019). To define priorities, the participation of local communities is essential, and should promote a convergence of scientific and traditional knowledge (Herrero et al., 2020). The pace of the innovations can be increased, with the appropriate policies, incentives, regulations and social acceptance (Fanzo et al, 2020).

At the level of specific technologies, the range of possibilities is extremely wide, although two essential concepts stand out: greater precision and efficiency to produce more with less in a sustainable context (ECLAC et al, 2019; Trigo & Elverdin, 2019):

- Rapid and efficient improvement systems, based on the use of genomic information, generational acceleration, and molecular techniques like gene editing.
- Crop sensors connected to mobile devices that allow evaluating input (fertilization, water needs) at precise times and scales.
- Crop health monitoring systems and biological and artificial intelligence mechanisms, which will allow reduction of chemicals in the control of pests and diseases.
- Virtual strategies for the dissemination of management techniques adjusted by locality / region, to significantly increasing the integrated management of crops.
- Livestock biometrics; use of collars and other devices to monitor in real time information about behavior, consumption, and general condition of the animals.
- Precision agriculture, which integrates agroecological and productive information with ICT, proposing management strategies to optimize the use of inputs, including improvements in the efficient use of water and the use of sensors for micro-administration of irrigation.

In addition, there are significant advances in use of beneficial soil microorganisms in agriculture, and the application of the microbiome that can provide higher and more sustainable levels of productivity improvements, food quality and profitability (Singh et al., 2020, FAO, 2019,). Strong international cooperation in microbiome science is essential for achieving efficient microbiome-based innovations (D'Hondt et al., 2021).

A perspective from Latin America and the Caribbean

The LAC region is not only a great producer of sustainable biomass, it has become one of the main actors in international markets due to important developments in its scientific-technological capacities, industrial infrastructure and bio energy generation. Several significant technology developments provide a platform of great importance when facing future challenges. These not only include traditional and export crops, but also agricultural biotechnology applications, conservation and regenerative agriculture and sustainable livestock production systems (ECLAC et al., 2019, Trigo & Elverdin, 2019). In biotechnology applications, the region has been one of the early leaders in the adoption of agricultural biotechnology (GM crops) (www.isaaa.org). There are successful public-private initiatives resulting in close to market developments in strategic crops such as soybeans, common beans, potatoes and wheat, and more recently in rice, through the application of gene editing technologies (ECLAC et al., 2019; Oliva et al., 2019).

Another development worth mentioning is the emergence of a new generation of young entrepreneurs, developing technologies and start-ups in several countries (e.g., Mexico, Costa Rica, Colombia, Peru, Brazil, Argentina, and Uruguay). These are beginning to have an impact on the regional bioeconomy landscape, and creating new pathways for scientific effort benefiting the region. A non-comprehensive list include:

Protera. A Chilean biostartup developing safe, sustainable, and smart protein-based food ingredients with Artificial Intelligence applied to synthetic biology (https://www.proterabio.com/technology)

Hemoalgae. A Costa Rican biostartup developing high added value chemical compounds using microalgae-based production platforms (http://hemoalgae.com/).

Nutriyé. A Mexican biostartup developing functional beverages using nutraceutics and natural biological compounds and exploring the potential of personalized nutrition (http://www.nutriye.com/).

Syocin Biotech. An Argentinian startup developing synthetic biology platforms to redesign and produce biomolecules to target plant bacterial pathogens (http://syocin.com/).

Sciphage. A Colombian startup developing bacteriophage-based solutions to treat bacterial infections in poultry and reducing the use of antibiotics. (https://sciphage.com/)

Eficagua. A Chilean biostartup developing solutions to optimize the use of water in agriculture (https://eficagua.cl/).

Oxcem. A Peruvian biostartup creating microalge-based systems to address air pollution in big cities (https://oxcem.com).

Scintia. A Mexican biostartup developing innovative tools to make biotechnology and synthetic biology more accessible (https://www.scintia.com/).

In the case of conservationist and regenerative agriculture, reduced tillage practices have been adopted in a wide diversity of production systems (ECLAC et al 2019). There are also important initiatives directed to highlight the strategic character of soils, such as IICA's "Living Soils of the Americas", which seeks to connect public and private efforts in the fight against soil degradation and to maintain the health of cultivated land as well as an efficient management and conservation of soils (https://iica.int/en/press/news/rattan-lal-and-iica-launch-living-soils-americas-initiative). As mentioned crop diversification using local varieties is a strategy to face climate change, improve nutrition and increase resilience (ECLAC et al, 2019).

LAC countries are highly vulnerable to climate change because of their socioeconomic, geographic and institutional characteristics (ECLAC-UNDR, 2021), which is very important for the agricultural sector. Natural disasters such as flooding, storms and landslides are increasing, and several international agencies (UNEP, WFP, CGIAR) are working to promote climate resilience, reforestation and restoration. For instance, the mandate of CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is to identify and address the most important interactions, synergies and trade-offs between climate change, agriculture and food security. Some results are presented in an Inventory of CSA practices in LAC Climate Smart Villages (Bonilla-Findji et al., 2020). Some studies show that by implementing integrated soil and water management strategies, smallholder family farms can become resilient to climate change (Roop & St. Martin, 2020).

The Caribbean region economies are dependent largely on tourism (ECLAC-UNDR, 2021) and most all the Caribbean countries are net food importers despite having arable lands, rich agrobiodiversity and favorable growing conditions. As agricultural production has been declining in 2018 the Caribbean Community formulated a strategic plan to promote sustainable food production and reduce import dependency through innovation and modernisation of agriculture (https://caricom.org/). The objectives are increased employment, poverty alleviation, reduction in the import bill, food and nutrition security and a reversal of the growing incidence of chronic non-communicable diseases. CARDI will promote the adoption of climate smart agricultural practices by pursuing effective partnerships, capacity building opportunities and information generation and dissemination

(CARDI 2018).

The expanding aquaculture industry (the farming of aquatic organisms including fish, mollusks, crustaceans and aquatic plants) can provide more sustainable animal source foods (Gephart et al., 2021) and is contributing to the regional economy through more than 200,000 direct employments and 500,000 indirect ones. In 2018 aquaculture in the Americas produced 3,799,191 tonnes of animal and 21,984 tonnes of plant material (FAO 2020b).

Despite these important developments, the overall picture in the region is one of concern, as a majority of the countries in LAC, particularly the smaller ones, are on the sidelines. They reflect a 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 S&T. In terms of investments, five countries (Argentina, Brazil, Chile, Colombia and Mexico) account for more than 90% of the regional investment (Stads et al., 2016). The same trend is observed when investment is presented in terms of a percentage of the countries' agricultural GDP. Only six countries -Brazil, Chile, Anglophone Caribbean, Uruguay, Argentina, Costa Rica and Mexico- invest more than 1% (Stads et.al., 2016). These figures are closely associated with the productivity gaps that are becoming increasingly evident between the region and the rest of the world, and between the tropical and temperate areas (Nim-Pratt el al., 2015). They are also in marked contrast with other countries with relevant agricultural sectors, such as Canada, where investment in agricultural R&D as a percentage of agricultural GDP amounted to 11.3% (2009), or in Australia it exceeded 12.5% (2011) (OECD, 2018).

A similar picture is seen with investments in and capacity for the biosciences. At best, most countries are in the early stages of effectively using new technologies, with significant investments concentrated in a small number of the larger countries, so much of the region's agriculture risks losing the benefits of the new technologies. Close to 90% of total investments and applications in biotechnology in LAC were in Brazil (>50%), Argentina, Mexico, Venezuela, Chile and Colombia (Trigo et al, 2010). This low and concentrated investment levels, is also reflected on the availability of human resources, and issue perhaps more strategic due to the increasing complexity of the situations to be faced. (Stads, et.al, 2016).

Lessons from COVID-19

The confinements and disruptive effects caused globally by COVID-19 have demonstrated the enormous fragility of our agrifood systems, stressing the need for FS transformation (UN 2020). The pandemic caused disruptions to global food supply, stressing the crucial importance of LAC as provider of food, and pointed to the need for promoting greater intra-regional economic cooperation, in terms of production, trade and technology (Morris et al., 2020). In this sense, the current crisis is a unique opportunity to change the false claims that economic growth is conflicted with environmental sustainability, and to apply the bioeconomy approach for territorial development with circular systems, and greater resilience for the benefit of society and the planet (Trigo et al., 2021; Lachman et al., 2020). In most LAC countries, FS responded well and was able to continue providing food throughout the crisis, with a rapid emergence of alternatives distribution and marketing systems, through partnerships and the use of the internet (IICA, 2021).

However, as in other parts of the world, the pandemic has triggered recession and declines in income, especially of poor people and due to some disruptions in the food chain vulnerable groups suffered with respect to food security and nutrition . For example, young people in LAC have had difficulty accessing healthy foods such as fruits and vegetables, compounded by decreased physical activity and increased the consumption of sugary drinks, snacks and fast foods (Leon & Arguello, 2021). The use of Information and Communication Technologies (ICT) and e-trade have grown rapidly. Overall, the insights and lessons from the pandemic should help to design better policies and build more resilient and inclusive food systems for the future. (Swinnen. & Mcdermott, 2020). Looking to the future, a key issue to be confronted will be the fiscal consequences of the COVID-19, as many countries are already making significant cuts into their R&D investments, imposing new restrictions to already poorly financed science and technology systems (IICA, 2021).

Moving forward: Strengthening policy in LAC for research and its uptake

Present STI scenarios offer and extensive and strategic set of opportunities and instruments for FS transformation. However, in most cases, existing institutions and orientations reflect past situations and priorities (Morris et al, 2020), and this is a negative factor for effectively mobilizing resources towards transformative Agenda 2030 objectives. Increasing investment levels is a common requirement for all countries, but beyond that, there is an urgent need for institutional structure and organizational approach better reflecting the new environment. The following paragraphs offer some reflections on specific topics and areas of work to consider for this purpose.

The institutional framework for innovation and transfer of agricultural technology:
STI alone cannot achieve all the advances in FNS required for the future. Developments, combined with evidence-based policy, must be implemented in the Americas. There is a need for better integration of STI progresses and investment opportunities to national policy making and communicating its potential to the public (IANAS, 2018). R&D institutions should address sustainable whole food systems in an integrated way and along interconnected value chains (HLPE, 2019). Achieving sustainable FS needs the full support of diverse policies: agricultural, trade and exchange, related to resources such as land and water, education and labor, financing and also the ones related to human health and safety, as well as permanent incentives. The goal is to deliver sustainable growth, good jobs, food and nutrition security, and climate-resilient ecosystem services (Morris et al, 2020).

Conventional approaches have resulted in a "silo institutional approaches" (Trigo & Elverdin 2019), which is not the most appropriate to face the complex challenges posed by food system transformation. There is a need to incorporate new actors into the process, and facilitate interaction between biological sciences and other areas of knowledge. There is little tradition of cooperation; therefore, advancing integration mechanisms around common objectives is a priority. Reconfiguring the relationship between scientific research and local knowledge systems is essential for the needed innovative transition pathways adapted to each type of agricultural and food system (HLPE, 2019).

Work and investment priorities:
In general, R&D priorities have been highly focused on solving production problems, improving resource management, and above all in a "short vision" of the agricultural and livestock sector (Stads, et al 2016). The new scenarios demand for a broader agenda, going beyond production to integrate issues related to sustainability, the entire supply chain value, quality, nutrition, energy production and industrial use of biomass (HLPE, 2019). Agriculture and food systems offer opportunities to generate significant numbers of high-quality jobs. It is imperative to direct investment toward sectors that are strategic for the big push, which also have a high potential for job creation (ECLAC, 2021). When technology meets a recognized need and is cost-effective for the intended beneficiary, uptake can be rapid (Fanzo et al, 2020). At the same time, experiential learning and knowledge sharing among practitioners, and co-production of knowledge among multi-stakeholder networks, should be recognized as effective approaches to generate the type of well adapted to the local context innovations that are needed, and to enhance their rapid adoption (HLPE, 2019).

Dealing with the distributional effects of the new scenarios and public policies:
Technological change has consequences and effects on the competitiveness of the sector. Innovation must be complemented by policies and actions specifically aimed at ensuring the equitable participation of all sectors involved, particularly those sectors of small-scale family agriculture with restrictions in terms of availability of resources and/or access to infrastructure or services. In this regard, agenda priorities should consider: (i) policies and actions aimed at promoting more equitable access to new technologies (credits, training, development of strategic infrastructures, subsidies to providers of certain technological services, etc.). (ii) the strengthening of national research and development institutions technologies, so that they can be more effective in helping to correct existing market failures affecting equitable access to new technologies.

Improved international cooperation mechanism:
The nature of FS calls for an integrated and multi-disciplinary approach including aspects related to the use of natural resources, the adoption of new technologies as well as the issues related to food demand and human behaviour. Policies must respond to local conditions, capacities and cultures and consider the vulnerable groups, but also must be coordinated with global trends (Fears et al, 2020). To take advantage of the transformative potential of technology, it is essential to develop national/regional innovation ecosystems, with the support mechanisms and

necessary infrastructure to promote the high levels of agricultural innovation required for the future through the promotion of regional and international cooperation (HLPE, 2019).

For many countries, there are several limitations to access the benefits of new technologies and calls for improved cooperation mechanisms aimed at pooling capacities and technology sharing. It requires a more complex R&D agenda giving greater importance to basic research in innovation processes, as well as the generalisation (and internationalisation) of protection frameworks for the intellectual property of the new technologies. This is particularly the case for smaller tropical countries, where scale is not only affected by the size of their economies, but also because they often have greater agroecological diversity. In this context, when thinking about future strategy, the question of the size of economies and how that is reflected in capabilities, investment and scale of work of research institutions is an unavoidable issue. Related to this, the construction of solid linkage networks with regional public R&D systems and agricultural extension, and with the private sector, becomes fundamental when it comes to achieving greater efficiencies.

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This report presents an update and summarised version of the report Opportunities and challenges for research on food and nutrition security and agriculture in the Americas, available at https://www.interacademies.org/publication/opportunities-and-challenges-research-food-and-nutrition-security-and-agriculture.

The role of science, technology and innovation for transforming food systems globally

by Robin Fears and Claudia Canales Holzeis

Although much progress had been made in past decades, the prospects for food and nutrition security are now deteriorating and the converging crises of climate change and COVID-19 present major risks for nutrition and health, and challenges to the development of sustainable food systems. In 2018, the InterAcademy Partnership published a report on the scientific opportunities and challenges for food and nutrition security and agriculture based on four regional reports by academy networks in Africa, Asia, the Americas and Europe. These analyses and conclusions have now been updated as briefs to the UN Food Systems Summit. The present global brief draws on new evidence from the regions to reaffirm the continuing rapid pace of science, technology and innovation and the need to act urgently worldwide to capitalise on the new opportunities to transform food systems.

We cover issues for sustainable, healthy food systems in terms of the whole food value chain, including consumption and waste, the interconnections between agriculture and natural resources, and the objectives for developing a more balanced food production strategy (for land and sea) to deliver nutritional, social and environmental benefits. Our focus is on science and we discuss a range of transdisciplinary research opportunities that can underpin the UN FSS Action Tracks, inform the introduction of game changers, and provide core resource to stimulate innovation, inform practice and guide policy decisions. Academies of science, with their strengths of scientific excellence, inclusiveness, diversity and capacity to link between national, regional and global levels, are continuing to support the scientific community in playing a key role to catalyse action. Our recommendations concentrate on priorities for building the science base – including the recognition of the importance of fundamental research – to generate diverse yet equitable solutions in providing sustainable, healthy diets, which are culturally sensitive and attend to the needs of vulnerable populations. We also urge better use of the transdisciplinary science base to advise policy making and suggest that this would be greatly advanced by constituting an international advisory Panel for Food and Nutrition Security with particular emphasis on sustainable food systems.

Introduction: the transformation of food systems

The world is not on track to meet Sustainable Development Goal (SDG) targets linked to hunger and food and nutrition security. According to FAO data (FAO, 2020), the number of hungry people has increased by 10% in the past five years and 3 billion people cannot afford a healthy diet. Some countries in Asia and Africa have made significant progress in increasing food and nutrition security alongside reducing poverty in the past decade, but others have not (EIU, 2021). The risks continue to be compounded by the impacts of population growth, urbanisation, climate and other environmental changes, market instability and economic inequality. Furthermore, the COVID-19 pandemic has exacerbated problems and imposed disproportionate effects on the economically vulnerable including marginalised groups in urban areas and smallholder farmers in rural areas (FAO, 2020; EIU, 2021). However, while there are unprecedented challenges, there are also unprecedented opportunities to capitalise on science, technology and innovation to transform food systems.

In 2018, the InterAcademy Partnership (IAP), the global network of more than 140 academies of science, engineering and medicine, published a global report on food and nutrition security and agriculture, drawing on information from four regional reports prepared by academy networks in Africa (NASAC), Asia (AASSA), the Americas (IANAS) and Europe (EASAC) and emphasising the value of taking a transdisciplinary approach. In the present Food Systems Summit Brief, we present an update on some of the issues from that global report linked to the recent assessments made in the Briefs prepared by the regional academy networks for the UN FSS.

The work of the academies has adopted an integrative food systems approach, along the value chain encompassing food processing, transport, retail, consumption and recycling, as well as agricultural production. Moreover, in the transformation of food systems towards economic, social and environmental sustainability, setting agricultural priorities must take account of climate change and pressures on other critical natural resources, particularly, water soil and energy, and the continuing need to avoid further loss in ecosystem biodiversity. Interest worldwide in the sustainability of food systems is accelerating (e.g. Global Panel, 2020; IFPRI, 2020; Food Systems Dashboard, 2020; von Braun et al., 2021).

In this Brief, that covers the opportunities and challenges for food systems in tackling malnutrition in all its forms (undernutrition, micronutrient deficiencies, overweight and obesity), we frame the contribution that science can make to local-global connectiveness of food systems: (i) to strengthen and safeguard international public goods, i.e. those goods and services that have to be provided at a scale that is beyond individual countries or that can be better achieved collectively; (ii) to understand and tackle environmental and institutional risks in an increasingly uncertain world; and (iii) to help to address the SDGs by resolving complexities of evidence-based policies and programmes and their potential conflicts.

Regional heterogeneity

Inevitably, in a summary of the global position, it is difficult to capture the diversity within and between regions relating to the challenges for food systems. The regional Briefs by the Academies have indicated the territorial dimension in analysing obstacles to food and nutrition security, emphasising specific contexts for marginalised peoples and smallholder farmers, e.g. for the Hindu Kush Himalayan region (AASSA, 2021). In Africa, although remarkable progress has been made in the last two decades in reducing extreme hunger, there are increasing pressures on food systems that require radical action (discussed in detail in NASAC, 2021). Most African Union member states are not on track to achieving the Comprehensive Africa Agricultural Development Plan goals (African Union, 2020). In the comprehensive publication on country-level data in the Americas that accompanied the regional report on food and nutrition security and agriculture (IANAS, 2017, regional update IANAS, 2021), there was detailed discussion of diversities within the region and of variation in the social determinants of food and nutrition security, e.g. related to gender. Other regional assessment finds moderate-severe food insecurity (SDG Indicator 2.1.2) across the FAO Europe-Central Asia region, varying from 6.7% in the EU to 19% in the Caucasus. Obesity throughout this region is higher than the world average [VII], a challenge that has been examined by EASAC (2021).

Agriculture-environment nexus

IAP defines the desired outcome for food systems as access for all to a healthy and affordable diet that is environmentally sustainably produced and culturally acceptable. The IAP report in 2018 cautioned that an emphasis on increasing total factor productivity (TFP, the efficiency in use of labour, land, capital and other inputs) is not warranted if such a focus leads to reductions in environmental protection. Since then, there has been continuing interest in using research to leverage TFP for sustainable and resilient farming (e.g. Coomes et al., 2019). In particular, the paradox of productivity has been highlighted (Benton and Bailey, 2019) whereby agricultural productivity may generate food system inefficiency. That is, productivity, when leading to increasing availability of cheaper calories, may help to promote obesity although nutritional content matters as much as calories. Current global competition policies incentivise producers who can produce the most cheaply, typically with environmental damage, including biodiversity loss (Chatham House, 2021). The strategic focus of research and development, as well as production systems, should shift from staple crops with the current emphasis on production of a narrow range of calorie-intensive staple crops to a balanced strategy for crops that are of more value in terms of nutritional, social and environmental benefits, including fruit, vegetables, seeds, nuts and legumes (as food and feed, NASAC, 2021).

Reform of food systems requires decision makers to recognise the interdependence of supply-side and demand-side (including dietary change and waste reduction) actions. There must be further consideration given to strengthening coherence between global agreements, e.g. on responsible investment, and national action (Chatham House, 2021). And, the continuing food system sustainability challenge to balance production objectives for agricultural exports with satisfying domestic food and nutrition requirements is an issue for some countries (e.g. IANAS, 2021).

Current intensive agricultural production depends heavily on fertilisers, pesticides, energy, land and water with negative consequences for environmental

VII FAO, 2020 "Sustainable food systems and healthy diets in Europe and Central Asia." ERC/20/2, on www.fao.org/3/nc226en/nc2262n.pdf. This report discusses multiple issues for diversified and sustainable food systems, improving supply chains and reducing food loss and waste.

sustainability. Changing environmental conditions and competition for key resources such as land and water provoke violence and conflict, exacerbating the vicious circle of hunger and poverty (NASAC, 2021). Discussion in the NASAC 2021 Policy Brief exemplifies some of the particular issues for managing water demand, including conservation and recycling of waste water and notes the opportunities for science, technology and innovation in new irrigation schemes. Research and innovation play a crucial role in the transformation to sustainable food systems to produce more efficiently by environmentally friendly means. The options for convergence of technological and societal innovation (including outputs from biotechnology, AI, digitalisation, and from social and cognitive sciences), exemplified later in this Brief, help to underpin the objectives for sustainable food systems.

Agro-ecology encompasses various approaches to using nature-based solutions for regenerative agriculture innovation (HLPE 2019) and systems research still needs to help strengthen the evidence base for agro-ecological (nature-based) approaches. For example, agroforestry in sub-Saharan Africa has potential to help tackle health concerns associated with lack of food and nutrition security (non-communicable diseases) and with human migration but requires additional research to characterise any increased risk from infectious disease alongside the beneficial outcomes (Rosenstock et al., 2019).

Developing diverse and resilient production systems worldwide is important in preparing for the likelihood of cumulative threats from extreme weather events by spillover across multiple food sectors on land and sea (Cottrell et al., 2019). In this context, it is relevant to note the interest in the potential of oceans for sustainable economies in addressing food security, biodiversity and climate change. One of the UK Presidency's core themes for UN FCCC COP26 is "Nature" with objectives for sustainable land use, sustainable and resilient agriculture, and increasing ambition and awareness of the ocean's potential. This potential is also of great importance for the UN FSS Action Track on nature-positive production. By contrast with difficulties in expanding land-based agriculture, the potential for sustainable production of fish and other seafood is increasingly recognised (Lubchenco et al., 2020; Costello et al., 2020) and brings new possibilities for local livelihoods. Fish supplies provide 19% of animal protein in African diets (Chan et al., 2018, NASAC, 2021). However, currently one-third of the world's marine fish stocks are overfished (FAO, 2020). Realising the potential of the oceans requires technological innovation and policy reform for fishery management and governance, to restore wild fish stocks, eliminate illegal and unregulated fishing, and ensure sustainable mariculture to minimise environmental impacts. Oceans can contribute to climate change mitigation as well as to improved food systems but it is important to be aware of inadvertent consequences of policy action, e.g. adoption of industrial-scale aquaculture can be associated with rapid growth in GHGs (in China, Yuan et al., 2019). Genetic improvement of fish species may help to reduce the environmental footprint of aquaculture (for example, in Africa where aquaculture has been expanding at a faster rate than in some other places, NASAC, 2021). This exemplifies a general point about seeking co-ordinated policy across sectors to avoid unintended effects and negative trade-offs. Another example is provided by poorly-designed land use policies to increase bioenergy production, driving increases in land rent with negative implications for food and nutrition security (Fujimori et al., 2019).

Delivering healthy diets sustainably produced under climate change

An accumulating evidence base demonstrates that climate change exacerbates food insecurity in all regions by reducing crop yield and their nutritional content and by posing additional food safety risks from toxins and microbial contamination (e.g. IPCC, 2019; Park et al., 2019; Ray et al., 2019; Watts et al., 2021). Effects are most pronounced in those groups who are already vulnerable, e.g. children, because of reduced nutrient intake (Park et al., 20190 or decline in diet diversity (Niles et al., 2021). A systematic review of the literature identified climate change and violent conflict as the most consistent predictors of child malnutrition (Brown et al., 2020). By increasing the volatility of risks in the global food system, climate change may also reduce the incentive to invest (IAP, 2018), and rising heat- and humidity-induced declines in labour productivity reduce the income of subsistence farmers (Andrews et al., 2018).

Although better international integration of food trade can be a key component of climate change adaptation at the global scale, it requires sensitive implementation to benefit all regions (Janssens et al., 2020): in hunger-affected export-oriented regions, partial trade integration may exacerbate food and nutrition insecurity by increasing exports at the expense of domestic food availability. When assessing trade implications, it is also important to appreciate that climate change presents a risk to global port operations with the greatest risk projected for ports located in the Pacific Islands, Caribbean Sea, Indian Ocean, Arabian Peninsula and the African Mediterranean (Izaguirre et al., 2021).

There are twin overarching challenges for food systems: how can they adapt to climate change and, at the same time, reduce their own contribution to GHG emissions and climate change? These intertwined challenges are discussed in all the regional assessments. Multiple scientific opportunities are identified to adapt by developing climate-resilient agriculture, e.g. from the application of biosciences to breed improved crop varieties resistant to biotic and abiotic stresses, and of the social sciences to understand and influence the behaviour of farmers, manufacturers and consumers in responding to climate change (see, for example, EASAC, 2021). Combining evidence-based measures will also be essential to mitigate GHG emissions from the sector (currently contributing approximately 30% of global GHGs, Watts et al., 2021), including improved agronomic practices, reducing waste, and shifting to diets with lower carbon footprint. For example, a background paper prepared in 2020 for the SBSTA of UN FCCC COP[VIII] explored agronomic case studies (in South America, Asia, Africa and Europe) for managing nitrogen pollution (including the powerful GHG nitrous oxide) and improving manure management to decrease GHGs and benefit the environment. Capitalising on such research requires better connections between science and the broader community and with relevant policy processes. There is particular need to dismantle obstacles for transferability of practices and scaling up of local research results to guide decision making at national and regional levels.

One major mitigation opportunity discussed by IAP (2018) and in all the regional assessments relates to the potential to adjust dietary consumption patterns to reduce GHGs and, at the same time, gain significant potential health benefits (see Neufeld et al., 2021 for discussion of the definition of healthy diet). For example, there is evidence that reducing red meat consumption, where that is excessive, can improve population health (Willett et al., 2019; systematic review of the literature in Jarmul et al., 2020). Red meat supplies only 1% of calories worldwide, accounting for 25% of all land use emissions (Hong et al., 2021), though meat is an important source of protein, minerals and vitamins. The policies for reaching such consumption adjustments require more research to actually identify solutions. The proportion of excess deaths attributable to excess red meat consumption is highest in Europe, Eastern Mediterranean, Americas and Western Pacific (Watts et al., 2021). However, some populations consume sustainable diets that are meat-based, e.g. the Inuit Indigenous People in the Canadian Arctic: proposals for dietary change must be carefully designed, evidence-based and culturally sensitive in being adapted to circumstances and protecting nutrient supplies for the most vulnerable groups. It should also be acknowledged that the efficiency of livestock production varies according to farming system, such that conclusions, e.g., about the sustainability of pastoral cattle production may be different from those for feed-lot cattle production (Adeosogen et al., 2019; AASSA, 2021), and that livestock may be the only agricultural activity possible in dryland regions that do not support the cultivation of crops.

Although Africa accounts for the smallest regional share of total anthropogenic GHG emissions, about half of this is linked to agriculture, and is experiencing the fastest increase of all regions (Tongwane and Moeletsi, 2018; Latin America and South East Asia are also demonstrating rapid growth, Hong et al., 2021). As part of the whole systems approach, formulation of mitigation solutions must decouple increases in livestock productivity (and cereal productivity, Loon et al., 2019) from increases in GHGs. Progress is being made (e.g. in China, Cui et al., 2018; AASSA, 2021) and decoupling can be informed by better use of the research evidence available, e.g. for herd management, improving animal health, breeding new varieties (with better feed conversion and energy utilisation efficiencies), improved forage provision (e.g. NASAC, 2021) and by strengthening of targeted social protection mechanisms alongside more generic recommendations for dietary change (EASAC, 2021).

There are unprecedented scientific opportunities coming within range but there are also multiple obstacles to mainstreaming climate change solutions into food system development planning. Evaluation of obstacles in India (Singh et al., 2017) highlights limited access to finance, difficulties in accessing research and education, and delays in accessing weather information. Systematic review of the literature on smallholder production systems in South Asia (Aryal et al., 2019) notes weaknesses in the institutional

VIII SBSTA 52nd Session 2020. "Improved nutrient use and manure management towards sustainable and resilient agricultural systems". FCCC/SB/2020/1.

infrastructure to implement and disseminate available solutions: the application of science requires institutional change. At global scale, there is need for enhanced access to climate information and services for climate-resilient food security actions (WMO, 2019), e.g. to aid decisions on most suitable crops and planting times.

Responding to COVID-19

Climate change and COVID-19 are converging crises for health in many respects (Anon, 2021) including food and nutrition security. Observations early during the pandemic[IX] indicated that production of staple food crops during critical periods (planting and harvesting) was vulnerable to interruptions in labour supply; food processing, transport and retail were also affected early on, particularly the relatively perishable, nutritionally-important, fresh fruit and vegetables (Ali et al., 2020). Subsequent comprehensive assessment of consequences for global food security (Swinner and McDermott, 2020) has evaluated how adverse effects on local practice and routines are transmitted to longer-term impacts on poverty and food systems worldwide in increasingly interconnected trade and markets. In some cases, supply disruption has been aggravated by national decisions to restrict export of food[X]. The combined effects of COVID-19 on recession and food systems disruption are particularly detrimental to the poor (Ali et al., 2020; Swinner and McDermott, 2020 include case studies in Ethiopia, China, Egypt and Myanmar; NASAC, 2021). However, in some regions, food systems proved relatively resilient (IANAS, 2021) and there are also examples of good practice in new safety net programmes, including school feeding programmes that should be more widely shared and implemented. Tackling the consequences for child malnutrition is identified as a particular priority for action (Fore et al., 2020), as is attention to gender bias whereby women are suffering more adverse effects in consequence of COVID-19-changed household and community dynamics (Swinner and McDermott, 2020).

As emphasised by EASAC (2021), the pandemic has exposed the vulnerability of over-reliance on just-in-time and lean delivery systems, globalised food production and distribution based on complex value chains. Therefore, opportunities for increasing localisation of production systems should be re-examined. However, there is often a mismatch in the timescale needed to adapt to COVID-19 between the imperative for early action to protect vulnerable groups and the relatively slow policy responses (Savary et al., 2020). Capitalising on the scientific opportunities may help to minimise this mismatch, e.g. improving food safety and reducing post-harvest losses (IAP, 2018), implementing evidence-based social protection measures and using Information and Communication Technologies for e-commerce, food supply resilience, early warning systems, and health delivery. Post-COVID-19 initiatives on novel foods, and urban and peri-urban farming systems, can also strengthen food supply chains and create new livelihoods for expanding urban populations, although it is also important to understand and manage inadvertent consequences for rural employment and the environment (Ali et al., 2020).

Using science, technology and innovation to promote and evaluate action

Continuing with business as usual will not meet the objectives for transformative change. To reaffirm a core message from IAP (2018): there is urgent need to use currently available evidence to strengthen policies and programmes, and to invest in initiatives to gain new knowledge. Examples of what is possible are discussed extensively elsewhere (e.g. Fanzo et al., 2020; Lillford and Hermansson, 2020)[XI]. It is not the purpose here to provide a detailed assessment of transdisciplinary research priorities but in Table 1 we map some onto the UN FSS Action Tracks to emphasise new opportunities coming within range and the need for science to achieve its potential. Examples are illustrative, not comprehensive, more detail on these and other research priorities are provided in IAP (2018), the regional Policy Briefs and in sections 1-4 of this global Policy brief. There are also, of course, many interactions between research streams and objectives that cannot be captured in Table 1.

IX CGIAR's response to COVID-19. www.cgiar.org/news-events/all-news/our-response-to-covid-19.
X International Monetary Fund "Policy responses to COVID-19". https://www.imf.org/en/Topics/imf-and-covid-19/Policy-Responses-to-COVID-19.

XI See also repositories of recent literature e.g. Sustainable solutions to end hunger (https://www.nature.com/collections/dhiggjeagd); Sustainable nutrition (https://www.nature.com/collections/fibbgbiebc); and Socio-technical innovation bundles for agri-food transformation (https://www.nature.com/documents/Bundles_agrifood_transformation.pdf).

Table 1. The power of fundamental science	
UN FSS Action Track	**Examples of research opportunities**
1.Ensure access to safe and nutritious food for all	Clarifying scientific basis for balancing of food systems for a greater emphasis on nutrition not just calories; incentives to promote sustainable practices and products, and disincentives for foods with high environmental footprints or adverse health effects. Integration of local, regional and global scales for sustainability, including renewed emphasis on value of indigenous crops. Broad research agenda for the agriculture-environment nexus, including livestock biometrics. Plus, bio/chemical sciences to identify health value of novel foods, holistic properties of foods (interactions within complex food matrices and mixtures), and components not ordinarily considered as nutrients (such as flavonoids, probiotics, anthocyanins) (Kongerslev et al., 2017 for dairy products; Thorrez and Vandenburgh, 2019 for cultured meat; Nuffield Council on Bioethics, 2019 for ethical issues).
2. Shift to sustainable consumption patterns	Social sciences to understand demand-side issues, role of public procurement, value-driven consumption patterns (Smith et al., 2016; Cuevas et al., 2017; Eker et al., 2019; Laar et al., 2020). Using advances in food science and technology in food processing to reduce post-harvest losses (Lillford and Hermansson, 2020).
3. Boost nature-positive production	Understanding value and vulnerabilities of mixed farming systems; reduction in the use of external inputs (including antimicrobials); mapping and using soil microbiomics (Singh et al., 2020); conserving and using genetic diversity in breeding (FAO, 2019; Pironen et al., 2019). Realising the potential of the oceans (Lubchenko et al., 2020).
4. Advance equitable livelihoods	Big data capture, analysis and communication e.g. for precision agriculture (Hodson de Jaramillo et al., 2019; Basso and Antle, 2020), supporting smallholders and new livelihoods (FAO1)
5. Build resilience to vulnerabilities, shocks and stress	Earth Observation Sciences to monitor agronomic status and guide interventions at large scale (Jain et al., 2019), linked to other technologies for crop sensors, mobile devices and remote monitoring. Development of baselines, attribution methodologies, reconciling differences in temporal and spatial scales in measurement, increasing understanding of synergies and trade-offs. Plus, the broad research agenda for tackling climate change and COVID-19 in provision of equitable services, including health care and social protection.

Several general recommendations can be made:

- There is need to increase commitment to invest in fundamental science and then connect that to applications and align with development priorities. There is also an important priority to develop improved methodologies to understand the levers of change, including the attributes of "game changers". That is, how to attribute outcomes and impact to investments chosen and scientific or other actions undertaken.
- There are new opportunities to improve collaboration and coordination worldwide, and build partnerships between public and private sectors, NGOs and other stakeholders to co-design and conduct research. Transdisciplinary approaches should be encouraged. There is increasing entrepreneurial activity worldwide, e.g. in the Latin America region a wide range of start-up company activities include novel foods, novel production systems, and novel approaches to optimisation of water and other natural resources (IANAS, 2021). There are also considerable opportunities in Africa for action on agriculture to

stimulate economic growth, reducing poverty, while also increasing food and nutrition security (Baumuller et al., 2021; NASAC, 2021).

- Training and mentoring of the next generation of researchers worldwide is essential: academies of science have a key role to encourage younger scientists.
- Obstacles, especially in LMICs, in the use and production of data and in scaling up applications must be addressed. For example, although big data/mobile-based communications bring significant benefits (e.g. IANAS, 2021; NASAC, 2021) and there are advances in using mobile technology to deliver climate services for agriculture in Africa (Dayamba et al., 2018), more should be done to increase access by small-scale farmers (Mehrabi et al., 2021). A digital inclusion agenda is needed for governments and the private sector to increase access to data-driven agriculture.
- In addition to generating excellent science, it is vital to reduce the delay in translating research outputs to innovation, public policy and practice (IAP, 2018). Time lags may arise from negative attitudes associated with perceived risks, by excessive regulatory requirements in some countries or by absence of regulation in others. This leads to fragmentation in the capture of benefits. For example, there is current heterogeneity in considering whether new plant breeding techniques – such as those based on genome editing – should be included within older legislation governing genetically modified organisms. Scientific advances are occurring worldwide, e.g. collaborative work in Colombia, Germany, France, Philippines and USA to develop rice resistant to bacterial blight (Oliva et al., 2019; IANAS, 2021). The controversy created by a situation where regulatory frameworks are disconnected from robust science is discussed by EASAC (2021). Figure 2 demonstrates the resulting incoherence that acts to deter science, innovation and competitiveness, creates non-tariff barriers to trade and undermines collective action to enhance food and nutrition security. This may have particular adverse consequences for those already suffering malnutrition; for example, the acceptance of gene-based technologies is mixed in Africa even though there may be considerable scientific opportunities for using biotechnology in crop breeding programmes to increase resistance to biotic and abiotic stress, improve nutrient content and nitrogen use efficiency (NASAC, 2021).

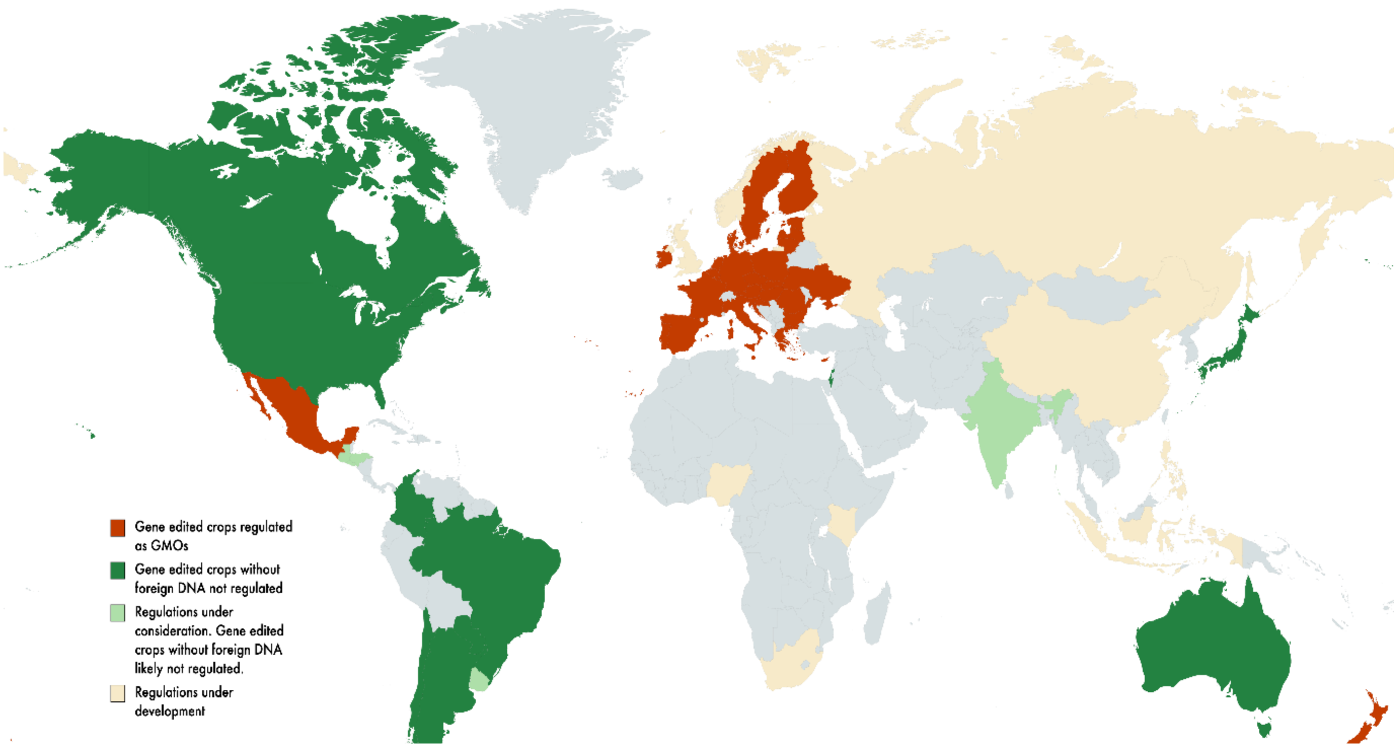

Figure 2: Variation in the regulation of genome editing for plant breeding.

Strengthening the contribution of research to policy making

Alongside action to accelerate investment in agriculture and food systems research (von Braun et al., 2020), there must be transdisciplinary integration of priorities at the science-policy interface across all relevant sectors (Fears et al., 2019), including agriculture, environment, health and social care, rural and urban development, and fiscal policy. There must also be linkage of policy at local, regional and global levels (Fears et al., 2020), while taking account of local values and circumstances and recognising the challenges for coordination. One recent example from Asia (Islam and Kieu, 2020) on developing critical mass in regional policy for climate change and food security discusses criteria for successive steps in policy planning, implementation, cooperation and legal obligation, and observes that the latter two steps often present fundamental barriers to moving from the priorities in a national development agenda to regional coherence. In the African region, the recent Joint Ministerial Declaration and Action Agenda (AU, 2020) calls upon governments to build greater productive capacity in agriculture and strengthen resilience throughout Africa's agri-food systems.

Scaling efforts for critical mass requires individual countries to recognise that their policy decisions may have impact on other countries and regions. For example, some countries export their lack of environmental sustainability by increasing food imports from elsewhere (IAP, 2018).

Academies and others within the scientific community (STCMG, 2020) have a key role in overcoming obstacles to effective policy by working together across disciplines to show the value of an inclusive approach, e.g. to the SDGs. Moreover, systematic review of the literature indicates that public support for a policy can be increased by communicating evidence of its effectiveness (Reynolds et al., 2020; Fears et al., 2020). Therefore, the work of academies to use the evidence base to inform policy development and implementation can help to provide the bridge between policy makers and the public.

What are the implications for the UN FSS? UN FSS discussions have highlighted the place of "game changers" for driving transformative action and the scientific community has much to contribute in exploring the potential of game changers to underpin transformation at the science-policy interface (see AASSA, 2021). For example, a recent commentary on Action Track 1[XII] identified some key precepts that can be illustrated by academies' work at regional and global levels (Table 2).

We suggest that there is an additional game changer, applicable to all Action Tracks: the development of a new international science advisory Panel on Food and Nutrition Security (IAP, 2018), with a broad remit for food systems, focused on shaping policy choices and strengthening governance mechanisms. A new Panel, recognising the new opportunities and challenges for food systems governance, could help to streamline research efficiency in its linkage to policy action and increase the legitimacy of that science advice by using robust assessment procedures (Global Panel, 2020). The impetus created by the UN FSS, requires the coordination and management of food systems by more sectors of government and stakeholders than had been the case for food security, bringing an unprecedented opportunity to develop a framework for greater transparency, accountability and sharing of knowledge. By consolidating the present myriad, fragmented, array of panels and advisory committees the proposed international advisory Panel could draw on the large scientific community already working on these topics – including academies – and should be asked to address the most pressing issues for transformative change in the face of the mounting global challenges. Food and nutrition security, particularly in high-risk groups, must be a top priority on all country's national agenda, yet many countries do not have a national security strategy in place (EIU, 2021). Furthermore, as already noted, advisory capacities, governance policies, and institutions are sometimes weak at the regional level (AASSA, 2021; NASAC, 2021). Thus, in addition to building the critical mass for evaluating complex issues at global scale, an international advisory Panel can help to drive momentum for a national food systems strategy in all countries and engender regional-level initiatives in policy development and implementation.

IAP recommends that the UN FSS now considers options for constituting a new international advisory Panel, to make best use

XII Haddad, L. 2021 "Food systems "game changers": reflections so far", on https://un-food-systems.medium.com/food-systems-game-changers-reflections-so-far-d4c8200c5663.

Table 2. The scientific community has a continuing role in assessing and implementing game changers to strengthen the contribution of research to policy making.

Game changers in Action Track 1	How are academies helping to inform policy options? Examples from the regional Briefs
Changing the fundamental incentives that created the present situation	Identifying research priorities for providing diversified, sustainable, healthy diets and pricing in negative externalities; developing better connections between data sets across health, environment and economics.
Taking advantage of shifts in underlying conditions	Clarifying consequences of COVID-19 in improving systems resilience and sustainable, equitable, healthy recovery.
Recognising value of multiple organisations working on related themes	Convening and catalytic roles to help reduce barriers between countries, sectors, disciplines and encourage shared perspectives.
Avoid neglecting the obvious	Reaffirming importance of current strategies for tackling all malnutrition, including fundamental science and food science and technology in support of innovation; paying more attention to understanding the value of indigenous crops (and improving their domestication) and traditional diets (e.g. in Africa, Mabhaudi et al., 2019).
Changing mind sets so as to think in terms of systems	Food systems approach has been central to the academies work in providing evidence to policy makers and other stakeholders, and in involving those whose voice has been sometimes muted.

of the rapid advances in science, technology and innovation, and to motivate evidence-based policy making at all levels. IAP and its regional academy networks are eager to be involved.

Conclusions

Achieving food and nutrition security worldwide by transforming food systems remains a major challenge, compounded by recent pressures from climate change and the COVID-19 pandemic. Actions to promote food systems are relevant to multiple SDGs. It is essential to identify opportunities for synergies and trade-offs while avoiding inadvertent negative consequences, and to engage everybody, to enable change. This requires advances in complex food systems modelling.

Food systems are diverse and heterogeneous. Continuing research is needed to inform diverse yet equitable solutions for sustainable, healthy diets that are culturally sensitive, focusing on vulnerable groups. That calls for stronger connections between local and international research entities. The opportunities of complex and innovative remote sensing and web-based data should also be explored for this purpose.

Greater transdisciplinarity is needed in research to progress from the current science agenda which is still too often focused on individual components of food systems or on agriculture separate from its environmental context. Social sciences research must be better integrated with other disciplines, e.g. to understand and inform consumer, farmer and manufacturer behaviours and to guide policies to deliver objectives for social justice. The development of improved methodologies for understanding attribution of impact is also a critical research priority.

Science is a public good yet the conduct and use of basic and other research is often fragmented. There is still much to be done to build critical mass worldwide, to share skills and research infrastructure and to collaborate in agreeing and addressing research priorities and avoid unnecessary duplication. There is a continuing convening role for academies of science to facilitate exploration of opportunities and tackle obstacles to research collaboration between disciplines and between the public and private research communities.

There are also opportunities to improve science-policy interfaces and integrate policy development at local, regional and global levels. One game changer would be to constitute an international advisory Panel on Food and Nutrition Security with new emphasis on food systems to make better use of the best science to inform, motivate and implement evidence-based policy making at all levels.

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