



Summary of **Socio-Technical Innovation Bundles for Agri-Food Systems Transformation**

**A Cornell Atkinson Center
for Sustainability/
Nature Sustainability
Expert Panel Report**

December 2020

**nature
sustainability**

Summary of Socio-Technical Innovation Bundles for Agri-Food Systems Transformation

A Cornell Atkinson Center for Sustainability–*Nature Sustainability* Expert Panel Report¹

December 2020

¹ The full report should be cited as Barrett, Christopher B., Tim G. Benton, Jessica Fanzo, Mario Herrero, Rebecca J. Nelson, Elizabeth Bageant, Edward Buckler, Karen Cooper, Isabella Culotta, Shenggen Fan, Rikin Gandhi, Steven James, Mark Kahn, Laté Lawson-Lartego, Jiali Liu, Quinn Marshall, Daniel Mason-D’Croz, Alexander Mathys, Cynthia Mathys, Veronica Mazariegos-Anastassiou, Alesha (Black) Miller, Kamakhya Misra, Andrew G. Mude, Jianbo Shen, Lindiwe Majele Sibanda, Claire Song, Roy Steiner, Philip Thornton, and Stephen Wood. Socio-technical innovation bundles for agri-food systems transformation, Report of the International Expert Panel on Innovations to Build Sustainable, Equitable, Inclusive Food Value Chains. Ithaca, NY, and London: Cornell Atkinson Center for Sustainability and Springer Nature, 2020. A brief comment based on the report appears in the December 2020 issue of *Nature Sustainability* (Barrett et al. 2020).

Executive Summary

Dramatic, global advances in human well-being have been enabled by technological and institutional innovations in agri-food systems over the past century. But these gains have increasingly had massive, adverse, and unsustainable spillover effects on climate, the natural environment, public health and nutrition, and social justice. How can we innovate to transition to agri-food systems that are healthier for all people and for the planet that must sustain current and future generations?

This report examines the scope for technological innovations to make agri-food systems healthy, equitable, resilient, and sustainable (HERS). The technological potential is huge, but no “silver bullets” exist because successful adaptation, scaling, and impact turn fundamentally on the specific biophysical, political, socio-economic, and cultural contexts of agri-food systems and on the human agency within value chains that drives production, processing, distribution, and consumption patterns. A successful innovation is unlikely to deliver in all contexts or on all objectives. Indeed, the creative destruction of technological change inevitably generates both winners and losers, both positive and negative spillovers across desirable objectives, and thus, opposition to innovations’ emergence and scaling.

Therefore, innovations do not diffuse independent of enabling market, regulatory, and sociocultural environments. Scaling promises technological advances and requires socio-technical innovation bundles of context-dependent, customized combinations of mutually reinforcing innovations. As much effort and investment is required to build the bundles as to develop the technologies at their core. Co-creation of bundled social and technological innovations customized to specific agri-food system contexts is essential if we are to navigate away from looming dangers and towards a HERS future.

This report concludes with seven essential actions to guide agri-food systems transformations:

- ▶ Develop socio-technical innovation bundles
- ▶ Reduce the land and water footprint of food
- ▶ Commit to co-creation with shared and verifiable responsibility
- ▶ Deconcentrate power
- ▶ Mainstream systemic risk management
- ▶ Develop novel financing mechanisms
- ▶ Reconfigure public support for agri-food systems

Report Summary

Technological and institutional innovations in agri-food systems over the past century have brought dramatic advances in human well-being worldwide. These gains increasingly appear unsustainable due to massive, adverse spillover effects on climate, natural environment, public health and nutrition, and social justice (Barrett in press). How can humanity innovate further to bring about agri-food system (AFS) transformations that can sustain and expand past progress, while making AFSs healthier for all people and for the planet that must sustain current and future generations?

Given projected growth in human populations and incomes, and the headwinds of the climate and extinction crises, satisfying future aggregate demand for food will put unprecedented pressures on finite water, land, genetic, and atmospheric resources. The risks of enormous and potentially irreversible ecological damage and of sociopolitical instability are no longer under serious scholarly dispute. These climate and environmental risks also imply potentially severe human consequences.

Furthermore, today's AFSs fail to ensure either healthy diets for all or equitable and inclusive livelihoods for the more than 1.3 billion people who work in agri-food value chains worldwide. Far too many people still face chronic or episodic undernutrition, diet-related health risks are a growing problem, and AFS jobs are among the most dangerous and exploitation-prone on the planet. The COVID-19 pandemic has laid bare the risks of excessive agri-food value chain (AVC) specialization and concentration, and the need for built-in redundancy as systemic insurance in the face of natural and manmade shocks that scientists expect will grow in frequency and severity in the years ahead.

This report was commissioned by the [Cornell Atkinson Center for Sustainability](#) in response to an invitation from the journal *Nature Sustainability*, which—in collaboration with its new sister journal, *Nature Food*—wanted to devote its 2020 expert panel to this topic. The panel brought together experts who come from many different continents and who span a wide range of disciplines and organizations—from industries and universities to social movements, governments, philanthropies, institutional investors, and multilateral agencies. Its task was to assess the current state of AFSs and the external drivers that will reshape them over the coming 25–50 years, to articulate a vision for AFSs at that 2045–2070 horizon, to review and synthesize the many emergent technologies that might help transform AFSs to achieve that vision, and to chart a strategy to transition from a perilous today to a healthier, more equitable, resilient, and sustainable tomorrow.

The Present and Likely Future States of Agri-Food Systems

The panel synthesized the best current science to describe the present state of the world's AFSs and key drivers of AFS changes over the next 25–50 years, as well as to tease out key lessons from the COVID-19 pandemic experience this year. As is increasingly widely recognized, **the costs that farmers and downstream value-chain actors incur and the prices consumers pay**

understate food's true costs to society once one accounts for adverse environmental, health, and social spillover effects. Inevitable demographic, economic, and climate change in the coming decades will catastrophically aggravate these problems under business-as-usual scenarios. Innovations will be essential to facilitate coordinated efforts to transition to more healthy, equitable, resilient, and sustainable AFSs.

AFSs consist of webs of interactions among human actors, non-human organisms, and abiotic processes, with complex interlinkages across trophic scales, economic sectors, geographic space, and time. **One must keep in mind four key features of AFSs, which we summarize in the mnemonic HHSS:** human agency, heterogeneity, spillovers, and science. The first and most important feature to recognize is the central role of **human agency**. AFSs reflect the interdependent actions of billions of decentralized actors, each pursuing objectives that may at times conflict with one another. Inclusive progress requires reconciling multiple, sometimes-competing objectives in pluralistic systems, often through the design of mechanisms to align incentives to induce mutually reinforcing cooperative behaviors.

The deep biophysical, political economic, and sociocultural **heterogeneity** of AFSs implies that the sociopolitical coordination mechanisms and the science necessary to craft beneficial innovations vary enormously across contexts. The diversity of AFSs is nicely summarized in the [Food Systems Dashboard](#) (Fanzo et al. 2020), on which we draw. One-size-fits-all solutions do not exist. Furthermore, the closely coupled nature of AFSs implies that innovations inevitably have unintended **spillover effects** elsewhere in the system. Coordinated portfolios of bundled social and technological innovations can attend to the varied objectives of the myriad actors who can accelerate or obstruct innovations, to obviate negative spillover effects that may arise from individual technologies, and to address complementary needs within heterogeneous AFSs. Finally, throughout human history, progress has come through **science**-based innovation, be it in biophysiochemical technologies (e.g., improved plant and animal genetics; or new medicines, transport, or computing equipment) or institutions (e.g., formal policies such as rules of tenure over land and water, or contract law; or informal sociocultural practices such as cuisine). The evolutionary nature of AFSs implies a constant need for generous scientific research funding to continuously innovate to adapt to evolving systems.

Although AFS innovations have enabled indisputable progress in living conditions over the past hundred years, contemporary AFSs appear utterly unsustainable, with massive, adverse spillover effects on the natural environment, public health, and social justice. Decades-long progress on reducing hunger has slowed and even reversed in some regions, due in large part to violent conflict and poor governance. While over 4.5 billion people, more than at any point in history, can afford a healthy diet, roughly 3 billion people cannot. Agricultural productivity growth has been critical to improving diets and reducing poverty, leading to real food-price declines, while helping to ease pressures on land use. Past patterns of agricultural innovation focused on boosting the supply of starchy staples, however, with underinvestment to assure sufficient supply of healthful foods such as fruits and vegetables. And sub-Saharan Africa benefited little from the productivity gains of the Green Revolution, which was better suited for Asian and Latin American contexts. Furthermore, slowing agricultural productivity growth,

worryingly high food loss and waste levels, and continued population and economic growth have contributed to increasing and more volatile real food prices this century.

Technological change in AVCs has often reinforced pre-existing inequalities, both geographically within and among countries, and in the division of gains between workers and the owners of land or capital. While AVCs employ more people worldwide than any other sector—more than 1.3 billion—AVC jobs are also more poorly compensated, dangerous, and precarious than those in any other sector save mining, and more prone to child, forced, and unsafe labor than those in any other sector but textiles. The share of employment and value added generated off-farm, in the post-harvest segments of the AVC, have grown especially rapidly. They have also been especially exposed to disruptions associated with the COVID-19 pandemic, especially in the food service sub-sector.

The sustainability and resilience of our AFSs are increasingly under threat. Agricultural output growth has been based in part on increased use of key inputs (e.g., water, fertilizers, pesticides, etc.), with concerning impacts on the climate, natural environment, and worker health. AFSs are major sources of greenhouse gas (GHG) emissions, although they have the potential to instead help solve the climate crisis, as rural lands could serve as a major GHG sink. Meanwhile, massive climate, pest, and policy shocks that disrupt agricultural production and markets have been growing in frequency, severity, and potential for co-occurrence with other shocks that compound damages.

The COVID-19 pandemic serves as both a warning and an accelerator. The COVID-19 pandemic has made it abundantly clear that healthy diets, equity, inclusion, resilience, and sustainability are interlinked issues that require collective action on a massive scale. Behavioral and cultural changes are needed as societies learn to do things differently, highlighting the key role of credible social influencers and thought leaders. The pandemic also provides us with an opportunity to address systemic challenges arising from other pressures, such as climate change, to which we have thus far been insufficiently responsive. We have only a short window of time in which to make AFSs far more health-promoting, resilient, equitable, and sustainable than they are now. We must be prepared for more severe and frequent, as well as simultaneous and cascading, shocks in the future. Crises inevitably spark innovation, and the pandemic has demonstrated we can mobilize massive resources quickly to fund both big science and expanded social protection when needed. Going forward, we need first-rate science and monitoring, backed up by communication, transparency, cooperation, and essential safety nets, to help us learn and adapt quickly while building and maintaining society's trust and strengthening the coordinating institutions necessary for effective response to systemic shocks.

As we look 25–50 years into the future, we must also keep in mind how very different tomorrow's world will inevitably look. **Three major, looming changes stand out, with serious implications for AFS and AVC innovations.** First, human population patterns are shifting. More than two-thirds of humanity will reside in urban locations by 2050, compared to a little over half today. This will require AVCs to reorient to serve cities, putting a premium on land-saving technologies (e.g., vertical farming, alternative proteins) that enable shorter supply chains.

Perhaps even more striking, global population should peak in the 2060s at roughly 10 billion people, with the vast majority of that growth occurring in sub-Saharan Africa as populations peak in Europe and east Asia this decade.

The second major driver will be income growth, especially in today's low- and middle-income countries. Patterns of future income and population growth imply that half or more of global food demand growth to 2100 will occur in Africa. Income growth will also fuel added consumer demand not only for nutrients, but more for non-nutritive attributes of foods—such as appearance, convenience, safety, social status, storability, taste, and variety—as well as for perceived environmental or social attributes associated even with the production process. This naturally concentrates value addition and employment growth in the post-farmgate portions of AVCs and gives downstream processors, manufacturers, retailers, and food service enterprises greater leverage to coordinate AFS innovation.

Third, significant climate change is already baked into our atmospheric systems due to GHGs of recent decades, just as there is considerable, dangerous momentum behind biodiversity loss arising from the confluence of habitat destruction and climate change. The existential threat posed by climate and extinction crises will compel a reorientation of food production away from heavy dependence on land and oceans so as to increase carbon sequestration in trees and soils, conservation of natural ecosystems to preserve wild species and buffer human populations against dangerous zoonoses, and production of renewable geothermal, solar, and wind energy to displace fossil fuels. This will steadily reduce the land and water footprint of food production, with capital increasingly substituting for land and water inputs. Together, these drivers imply a need to focus on Africa, on post-farmgate activities within AVCs, and on turning AFSs from a source of climate and biodiversity stressors to a locus of solutions.

A Shared Vision of Healthy, Equitable, Resilient, and Sustainable Agri-Food Systems

Having assessed the current state and external drivers of future AFSs, the panel then developed a shared vision for the AFSs of 25–50 years from now, beyond the 2030 horizon of the UN Sustainable Development Goals. Our shared vision encompasses four core AFS objectives: healthy and nutritious diets, equitable and inclusive value chains, resilience to shocks and stressors, and climate and environmental sustainability, summarized as HERS (Healthy, Equitable, Resilient, Sustainable). We must make what is already an immutably HHSS equally HERS. Failure to address the HERS objectives risks catastrophic failure, even existential threats, under business-as-usual scenarios. Faced with multiple, high-level, pressing objectives, AFS adaptations cannot attend only to unidimensional concerns, whether about climate, employment, environment, equity, health, productivity, or resilience. Both tradeoffs and synergies exist among these design objectives. Therefore, we need bundled responses to address looming challenges and to deliver



on the considerable promise of a rich pipeline of emergent technologies, a portfolio to bring about multiple objectives that no one innovation can simultaneously satisfy.

In order to enjoy HERS agri-food systems at a horizon of 25–50 years, we must invest and innovate now. We will reap then what we sow now. No one-size-fits-all innovations exist, however, to enable us to transition from the present, perilous state of AFSs to a HERS future. Many candidate socio-technical bundles are available, but those that can work in one system may be ill-suited for others. Appropriate paths from today to tomorrow necessarily differ by context. This requires paying close attention to five key balancing acts simultaneously:

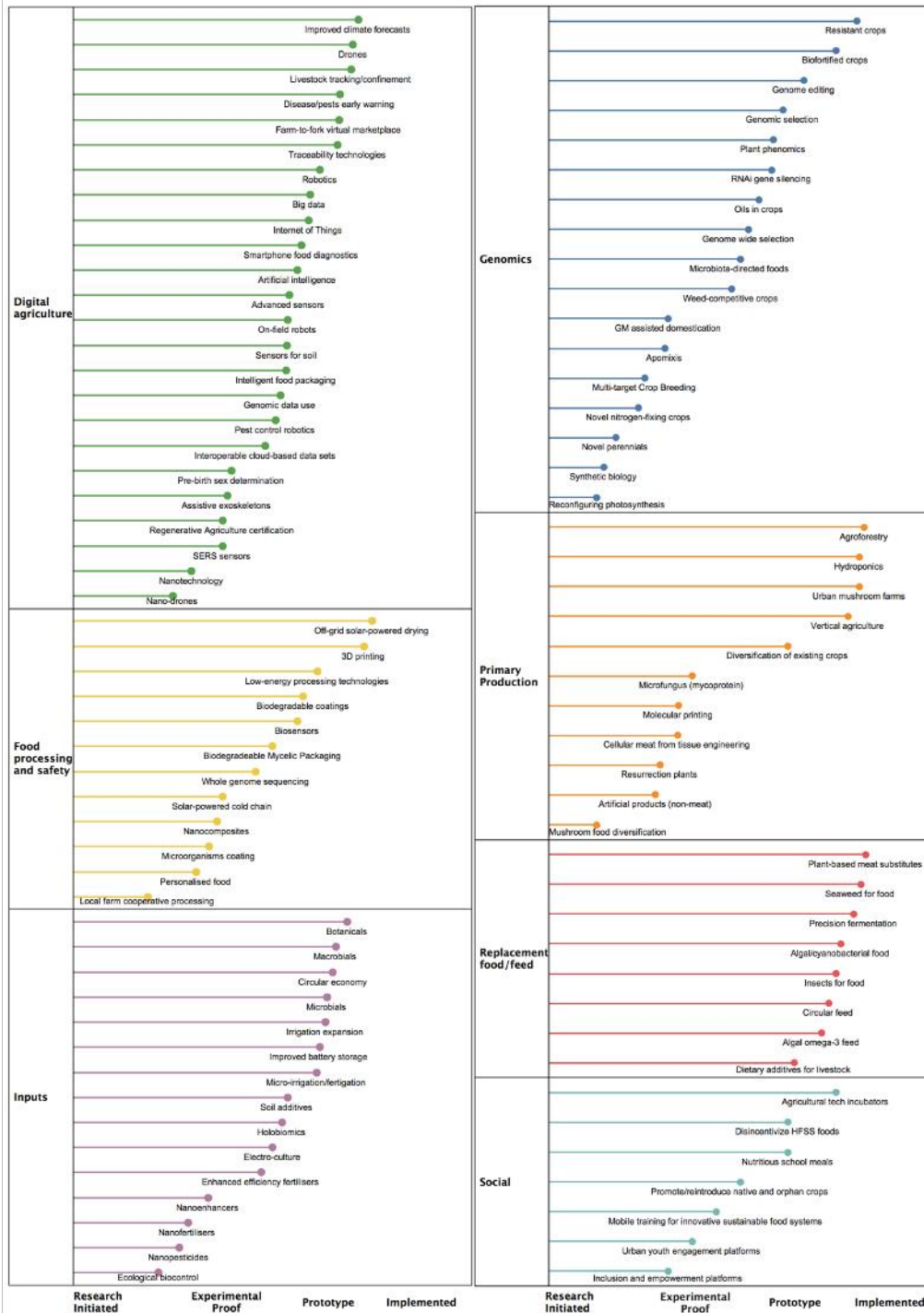
- ▶ Spatial extent of supply chains and food environments: weighing the benefits, costs, and risks of localized and global AVCs
- ▶ Scale of production: considering the gains from economies of scale and scope against the costs and risks of concentration
- ▶ Product diversity: balancing the benefits of diversification with the costs of complexity
- ▶ Functional diversity: weighing the added costs and prospective waste associated with redundancy against the resulting insurance against risk and concentrated market power
- ▶ Internalization of negative externalities: balancing reduction of the adverse environmental and public health effects of some AFS activities against the equity, health, and nutrition damages that can arise from raising the cost of foods

Each of these considerations comprises a spectrum that reflects trade-offs to be considered within each specific AFS context; there is no universal right answer.

A Profuse Pipeline of Promising Options

Building on Herrero et al. (2020), the panel studied scores of (natural and social) scientific and engineering advances at various stages of readiness for deployment, from initiatives well underway but not yet operating at large scale, to promising ideas still undergoing basic research. **A tremendous range of emergent options exist, spanning the full range of AVCs—from primary production through to final consumption and waste management—and drawing on a diverse array of sciences, from digital sciences through genomics, mechanical engineering, and the social sciences. Disruption opportunities abound.**

We grouped innovations under several headings. The first four represent innovations that cut across AVC stages—civic engagement, digital, financial, and social protection—followed by suites of innovations that largely follow the flow of food from upstream primary production in either sustainable animal and plant production systems or in alternative land-saving nutrient production systems, through supply chains, to consumer-level health and nutrition innovations.



Promising emergent technologies span scientific domains, AVC stages, and levels of technological readiness (adapted and extended from Herrero et al. [2020]).

Digital Innovations

Digital technologies are transforming AFSs along the entire AVC, revolutionizing how crops are planted, monitored, harvested, marketed, and consumed. **No segment of the AVC is untouched by digital innovation, and no other scientific domain is as replete with emergent**

innovations and start-ups. Behind this momentous shift lies the ubiquity of mobile phones—increasingly smartphones—in the hands of farmers, consumers, workers, and AVC entrepreneurs, alongside the plunging cost and increasing availability of wireless connectivity. Even very rural parts of the globe are rapidly being brought online, allowing farmers, traders, and workers to access various digital platform technologies. Meanwhile, advances in the Internet of Things, remote sensing, machine learning, artificial intelligence, and robotics are changing the face of agri-food production, processing, manufacturing, and distribution throughout the world. Collectively, these transformations across AFSs throughout the global North and South are promoting greater efficiency, farmer and consumer value capture, transparency, and traceability. They can also empower traditionally marginalized populations—smallholder farmers, small- and medium-sized enterprise owners, workers, and spatially distributed consumers and citizens—with increased information and services that can enhance agency and participation.

Nonetheless, this emerging digital ecosystem also grapples with multiple risks that could ultimately undermine the beneficial impact of emergent digital technologies. The proliferation of decentralized platforms, apps, and digital services creates the potential for data fragmentation and siloing, limiting the ability to solve problems that require holistic perspectives.

Interoperability challenges and market power enabled by intellectual property rights can restrict innovation and competition. Increased connectivity and transparency can threaten individual privacy and security. As such, **investments in the foundational digital ecosystem—enabling environment requires at least as much attention as do slick new devices, apps, and algorithms.** Policies must protect individuals' rights to their own data, and foster and maintain common datasets for public information—like weather and soil maps, or details on food biochemistry and safety—along with the necessary data architecture to facilitate collaboration to solve the challenges our AFSs face.

Innovative Financing

Attainment of the UN's sustainable development goals (SDGs)—and, at longer horizons, of the HERS objectives—will require massive financial investments, not only expanded public and philanthropic resources but even more, greater private funding. Recent estimates suggest that simply meeting the zero-hunger targets of the second SDG will require additional annual public expenditures of US\$30–35 billion from governments and donors, much of it focused on Africa, with the private sector contributing an additional US\$50 billion or so annually in the developing world alone. Closing this investment gap—much less the larger gap implied by the broader HERS objectives and a longer time period to transition AFSs through peak human population in the 2060s—will require financial innovations to mobilize and effectively deploy the required scale of resources. **Because most capital is privately held, mobilizing the necessary finance will require adjusting investor incentives to address environmental, health, and social justice externalities and to attend to needs in places where commercial demand is sharply limited by poverty.** A range of recent financial innovations show considerable promise

to scale, and thereby mobilize, considerable additional private investment in AFS R&D. This includes a broad class of impact investment vehicles (e.g., landscape bonds, conservation finance, social bonds) certified benefit corporation organizational forms that commit firms to pursue non-financial as well as financial goals, advance market commitments and prizes for key innovations, and the possibility of intellectual property modifications such as benevolent patent extensions. We summarize the growing instruments systematically targeting and deploying investment capital toward projects aligned to SDG principles and briefly discuss how these may be further tuned to incentivize additional resources flowing toward HERS-oriented innovations.

Innovative Social Protection Instruments

Transformation inevitably brings dislocation. Therefore, **facilitation of inclusive transformation requires effective social protection instruments so as to protect those who stand to lose out from creative destruction. Otherwise, the human costs of innovation become grave and can prompt damaging backlash and associated sociopolitical instability.** A wide range of social protection mechanisms already exist. Innovation is needed, however, to overcome longstanding, systemic discriminatory access to social protection, to redesign food-related social protection programs to better deliver or contribute to healthy diets, to mitigate the privacy and human dignity risks posed by digitization of social protection programs, and to build graduation objectives into designs so as to help beneficiaries envision a brighter future.

Innovations in Civic Engagement and Policy

The same risks of dislocation that necessitate innovations in social protection equally demand advances in civic engagement and the crafting and conduct of public policy. Agri-food systems are both highly complex and evolving very rapidly. Technical innovations tend to be “pushed” from the supply side rather than “pulled” from citizens seeking improved living standards. **Shifting from product-oriented solutions towards human-centered innovation requires both technological and institutional innovations that counter concentrated commercial and political power and advance greater civic engagement.** Digital technologies increasingly enable connectivity that can facilitate greater inclusion in shared governance and AVC innovation. Robust engagement, however, is limited largely by connectivity, which reinforces the need for universal rural broadband. As AFSs diversify, networks between producers, policy, and consumers become more complex, thereby requiring improved data collection, transparency, curation, and accessibility. Another area for transformative policy reform involves the transition towards a holistic view of socioeconomic performance and away from reductive monetary metrics. Adoption of more nuanced and holistic development metrics may incentivize a very different kind of innovative ecosystem, one that places the well-being of its people and the environment first.

Sustainable Animal and Plant Production Systems

Animal and plant production systems must be placed on a more sustainable footing, shifting from many producers’ dependence on non-renewable inputs to the implementation of systems that complement improved genetic material, irrigation, and safe agrochemicals use

with agroecological principles such as diversity and the circular economy (i.e., reduce, reuse, and recycle wastes). The dependency of many production systems on manufactured and mined fertilizers used inefficiently contributes to greenhouse gas emissions from agriculture, air, and water pollution, and limited input access for AVC actors in traditional, informal, and emerging AFSs. Recovery of nutrients and carbon from organic waste streams into agriculture can contribute to reducing pollution, increasing soil organic matter, and improving food safety and nutrient content. While genetics and breeding have contributed to past increases in productivity, more sophisticated, recent technologies have mainly focused on a narrow range of plant and animal species and traits, and have too often faced strong popular or political resistance. Genetic approaches can improve resistance to biotic and abiotic stresses, promote diversification at multiple spatial and temporal scales, and increase the nutrient content of foods. Technical advances must, however, be combined with appropriate regulatory and infrastructural innovations to effect beneficial AFS innovations. Adaptation and implementation to the variety of AFSs worldwide requires that producers, AVC intermediaries, and consumers are engaged, informed, and willing to support the needed transitions with investment and necessary behavioral changes.

Alternative, Land-Saving Nutrient Production Systems

At least four distinct classes of innovation are starting to facilitate a much-needed reduction in the land and oceans footprint of healthy diets and the migration of food production towards urban-based consumers who represent the largest, and growing, share of food demand. Most of the land reduction will likely come from reducing the use of large livestock that are relatively inefficient converters of crude plant protein and nutrients into high-quality, human-preferred proteins. There are four key strategies to achieve such transitions:

- ▶ Tap microbes and fungi to produce novel foods through “precision fermentation” processes, leveraging advances in fermentation, food science, and synthetic biology to design micro-organisms that produce complex proteins from inexpensive feedstocks
- ▶ Use microalgae, insects (e.g., black soldier fly larvae), etc., as substitutes for land-intensive oilseeds-based proteins and fishmeal
- ▶ Employ tissue-engineering methods to grow animal tissue outside the body—so-called “clean” or “cellular” meats—instead of raising and slaughtering live animals
- ▶ Deploy aero-, aqua-, or hydro-ponic methods in so-called controlled environment agriculture—“indoor” or “vertical” farming—to grow consistent-quality, high-value, short-cycle horticultural products that avoid many issues associated with climate change and diseases pressures.

Research increasingly finds these alternative systems are scalable, yield foods and feed of similar quality and safety to conventional foods, and potentially offer added health, environmental, and/or animal welfare benefits. The unit production costs of these novel alternative foods and feeds are all falling fast, and the shorter supply chains appeal to firms and consumers concerned about logistical disruptions, especially after the COVID-19 pandemic experience. These alternatives will likely become price competitive this decade, posing a

serious commercial threat to conventional farm producers. Incumbent producers are, therefore, already mounting legislative and regulatory battles over product labeling, zoning, etc., in an effort to slow or stall competition from alternative, non-farm sources. The competitive pressures these new methods generate will enable, and may financially compel, increased use of rural lands to farm carbon, solar, wind, and geothermal heat—not just crops and livestock—and provide ecosystem services for payment, thereby helping convert AFS from a GHG source to a sink and from habitat destruction to conservation. Without thoughtful policies to manage rural livelihood transitions, however, the creative destruction unleashed by these technologies threatens significant dislocation in rural economies. Smoothing those transitions offers a golden opportunity to repurpose the more than US\$700 billion/year in distortionary farm subsidies that governments worldwide currently provide. Those public funds could instead facilitate farmer capital investments in renewable energy structures, conservation, carbon sequestration, and digital technologies—and supporting market infrastructure—necessary to monetize those energy and environmental services, facilitating an inclusive, orderly rural transition.

Supply Chain Innovations

Much of the task of translating shifting food demand patterns into HERS outcomes will fall on value-chain intermediaries between primary producers and final consumers. Key supply chain innovations between the farm and the consumer include pre-competitive engagement of large-scale food and beverage supply chain actors with transnational governance bodies, civil society, and supplier networks to converge on measures and certifications in direct support of the SDGs and Science-Based Targets that may then be transparently communicated to consumers with on-package labeling standards. A second theme profiles food processing advances that improve sustainability, food safety, and nutrition while decreasing food loss and waste, including novel production advances for urban and peri-urban environments, biosynthetic expansion, and low-energy means of reducing water activity to preserve foods. In the realm of packaging, the need for innovations that provide preservation performance while being 100% recyclable, biodegradable, or compostable stand out. Lastly, we highlight the need for solutions that deliver resiliency to critical food-system port infrastructure at risk to incremental and storm-induced flooding impacts that threaten product movement, thus risking food shortages, increased waste, and short-term food-price inflation and volatility.

Health and Nutrition Innovations

A key outcome of AVCs is human health and nutrition. **Improvement in health and nutrition status is driven through the types of foods that make up healthy dietary patterns.** There are many innovations to improve diets and nutritional status through the creation of new foods that meet nutritional needs or contain health-promoting elements, supply chain and food environment innovations, and demand-driven innovations to better track human nutrition. New food technologies include genetic modification and biofortification of staple crops at the farm level; alternative proteins based on microbial or cellular alternatives to traditional foods; reformulated foods to remove unhealthy ingredients in highly processed, packaged foods or to

fortify staple food products with micronutrients; and 3D-printed foods customized to individual-specific needs. Promising innovations along the supply chain and within food environments include taxes on unhealthy foods and beverages or subsidies to increase the production and sale of healthy foods. Front-of-the-pack labels on food products can increase transparency of the nutritional content of foods, their source, and their environmental footprints for consumers. Tracing technologies including a blockchain of foods can also provide information to retail actors and consumers on the origins and safety of foods. Tracking individual diets and nutrition status through “personalized nutrition” combines a range of scientific advances that cumulatively provide highly personalized and targeted dietary guidance to individuals and medical professionals. The public health impact, accessibility, and consumer acceptability of these interventions, nonetheless, remain very much in question.

Tailoring Socio-Technical Innovations Bundles to Distinct Agri-Food Systems

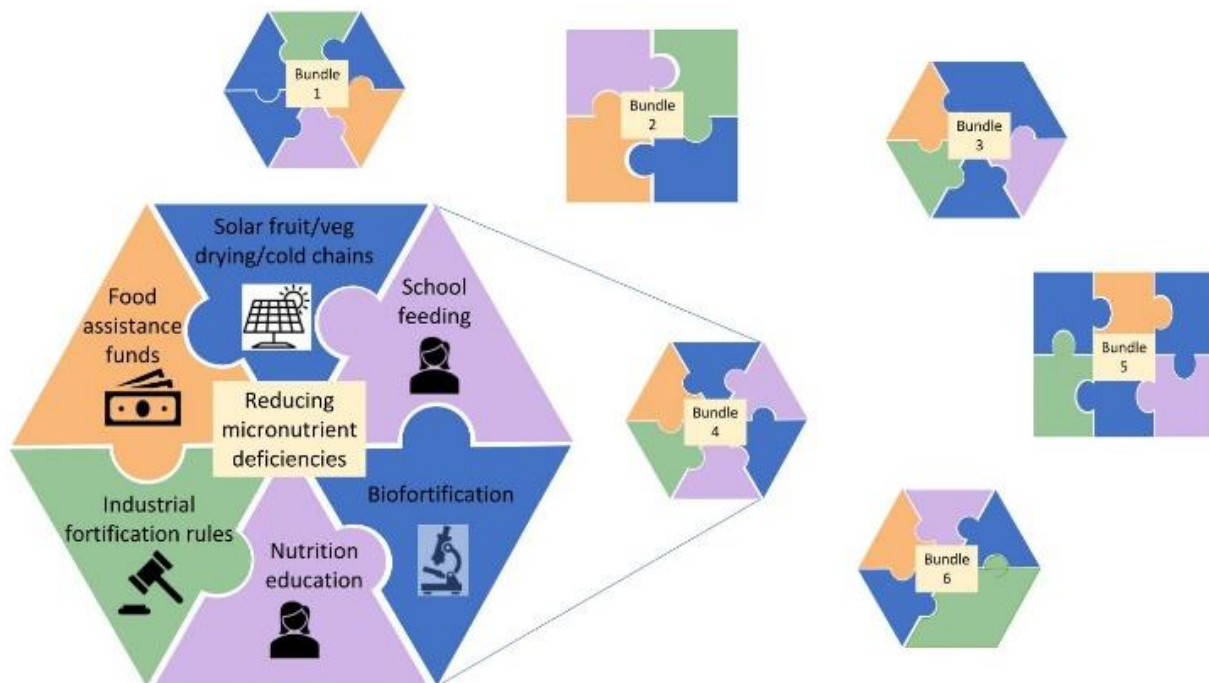
Socio-technical innovation bundles are essential for a balanced uptake of innovation. Despite the abundance of rapidly progressing, promising innovations across all stages of AVCs today, no magic scientific or engineering bullets exist. Few, if any, innovations can adapt and scale effectively without essential dialogue, consumer trust, and supporting policies and institutions to navigate a complex maze of biophysical, political economy, and sociocultural obstacles. And none can effectively target all four HERS objectives simultaneously. Indeed, the creative destruction of technological change inevitably generates both winners and losers, and new technologies almost surely generate both positive and negative spillovers across HERS objectives. Further, few, if any, technologies can address even a single objective on their own. Progress typically requires a combination of complementary innovations that can, together, get the job done. Stakeholders must, therefore, work together to build a bundle of complementary social and technological innovations so as to deflect opposition and obstruction, mitigate stark tradeoffs, and facilitate adaptation and up-scaling in order to deliver impact at scale across objectives. Co-creation of bundled approaches that combine contextually appropriate innovations is essential to enable packages of new technologies and practices to emerge, adapt, and diffuse to scale within and across contexts and to generate beneficial HERS impacts with limited or no unintended, net-adverse consequences.



Pathways to impact must be identified in advance to ensure that spillovers and perverse incentives are minimised. The pervasiveness of spillover effects and the enormous difficulty of simultaneously achieving uniformly positive outcomes across different development domains is a feature of trying to achieve all of the SDGs. Mapping and establishing paths to impact are essential to identify potential roadblocks or spillovers in advance. The panel could not identify a substantive

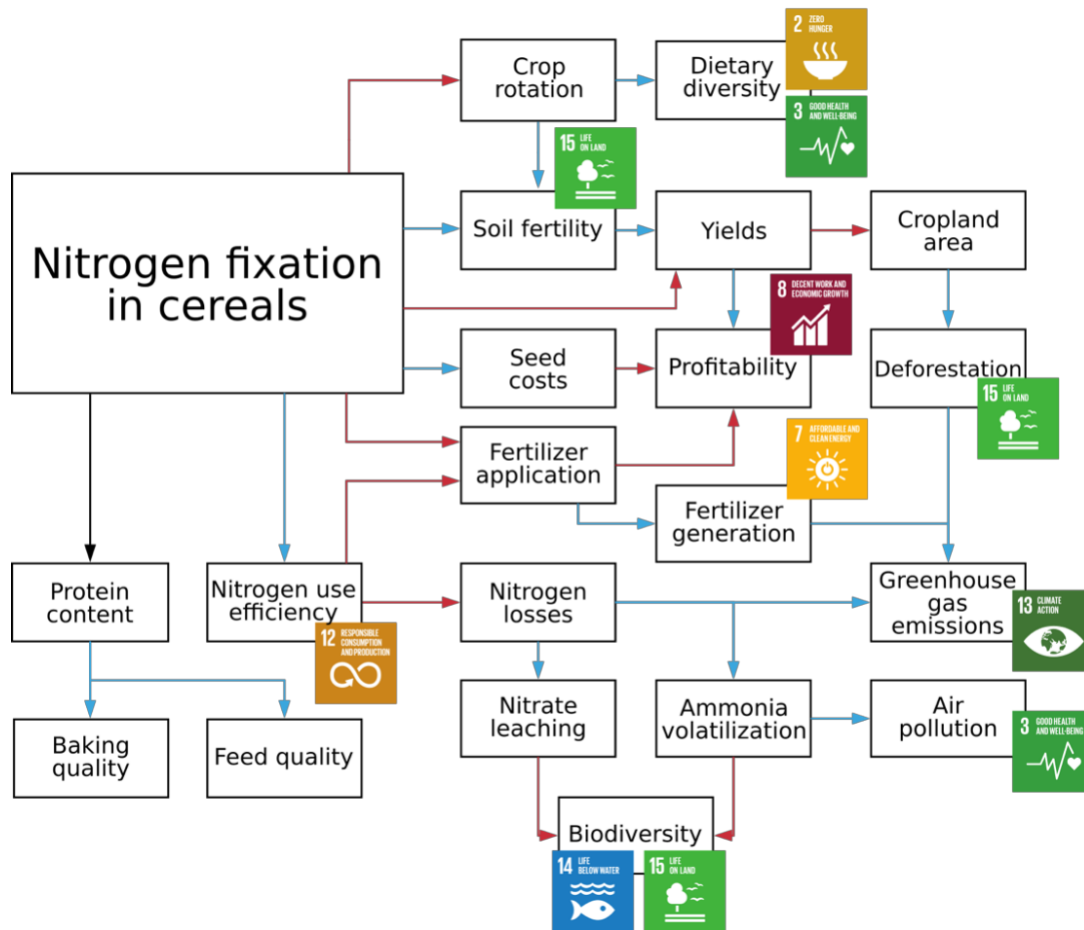
innovation that was not likely to have unintended impacts, positive or negative, on non-target outcomes. Even precisely targeted new technologies like nitrogen-fixing cereals will inevitably generate impacts well beyond the intended environmental and productivity outcomes.

Hence the need for bundling, for broadly participatory innovation processes, and for close monitoring of key indicators of AFS key performance measures (KPMs). We need to think not only of key accelerators and processes to ensure the adaptation and upscaling of impactful new technologies, but also of planning early in the adoption and diffusion process for corrective or compensatory measures to address negative, unintended spillover effects as and where they emerge. The complex pathways to impact illustrate the necessity of thinking in terms of socio-technical bundles for all upscaling processes and for achieving desired outcomes.



Distinct socio-technical innovation bundles must be tailored to different AFSs and objectives. The example illustrates ways of addressing mineral and vitamin (micronutrient) deficiencies in rural and traditional AFSs of the Global South.

In championing the central role of science and engineering to enable AFS transformation, too many high-level reports inadvertently downplay the equally central role of human agency. Therefore, we focus not only on the promise and risks of emergent innovations but just as much on the necessary actions by actors throughout AVCs. Change only comes about through the actions of people and the organizations they comprise. Impactful innovation—and obstruction of innovation—can originate among actors anywhere along the AVC, induced by any of a host of motives.

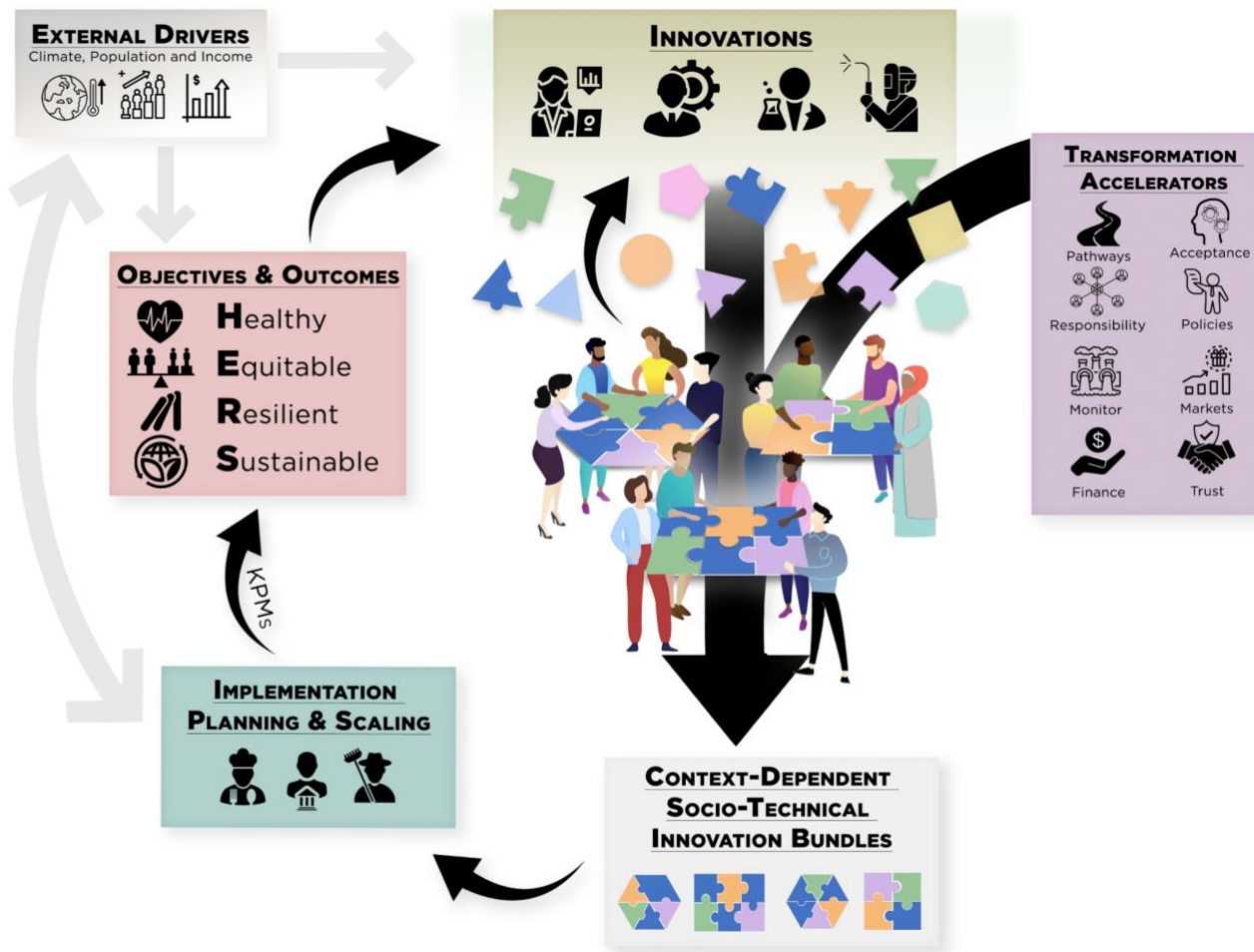


Pathways from an innovation to impacts are complex and inevitably spill over to affect multiple objectives. This example, from Herrero et al. (in press), traces the pathways from release of nitrogen-fixing cereals to various SDGs. It is essential to map likely impact pathways in advance.

What key players do in response to the wealth of emergent innovations will ultimately determine the path(s) we follow. Generating, adapting, and scaling fit-for-purpose socio-technical innovation bundles to advance HERS goals will, therefore, require coordinated actions. The many diverse actors within value chains must both empower each other and hold all parties accountable. Innovation co-creation is a strategic game in which each party's actions respond to others' behaviors. The challenge is to structure incentives and constraints so as to steer actors towards mutually beneficial actions, supported by key performance measures necessary to monitor progress and adjust course.

The panel, therefore, developed some process and action recommendations to guide AVC actors as we navigate together from the present, precarious state to a HERS for future generations. This requires some basic rules of engagement, including agreeing on a dashboard of key performance measures to monitor progress, and on sanctions and compensatory measures for transgression. Significant public investment and trust in first-rate science will be

necessary but far from sufficient. The institutional, policy, and sociocultural accelerators of technological adaptation, diffusion, and upscaling are essential complements. Hence the need for different AVC actors' active engagement in the AFS innovation cycle. A shared action agenda can generate superior, cooperative outcomes to the typically inferior outcomes that emerge from self-interested, non-cooperative behaviors. In order to harness the potential of the breathtaking pace of innovation today in digital, genetic, and other spaces, myriad AVC actors—consumers, retailers, restaurants, distributors, processors, farmers, input manufacturers, governments, charitable organizations, etc.—must engage in honest, constructive dialogues of the sort we undertook with the objective of co-designing contextually appropriate socio-technical bundles of innovations that can enable navigation away from looming dangers and towards a HERS future.



The panel's conceptualization of the agri-food system innovation cycle is depicted above. Human agency drives the AFS innovation cycle. External drivers (e.g., demographic change, income growth, climate change) influence collective objectives (e.g., HERS outcomes) and actor-specific objectives (e.g., firm profits or political power) and, jointly with those objectives, induce myriad innovations by individuals and organizations. Innovations (represented by puzzle pieces) draw on different (natural or social) science-based methods (represented by different

colors) to generate products, processes or policies with distinct designs and purposes (represented by different shapes). Transformation accelerators—key enabling societal features—help AFS-specific stakeholders redirect some ill-fitting innovations back for adaptation to the local context and accelerate the combination of other innovations. To become implementable and scalable, socio-technical innovation bundles need context-dependent pieces and the right composite shape. Implementation and scaling feedback on external drivers. The implementation and scaling, together with the external drivers, generate outcomes. Key performance measures reflect outcomes, informing assessment and adaptive management of synergies and tradeoffs among objectives. The AFS innovation cycle then begins again.

Seven Essential Actions to Guide Agri-Food Systems Transformation

The panel sums up its extensive review in seven essential actions to guide AFS transformations:

- ▶ **Develop socio-technical innovation bundles:** Despite the abundance of rapidly-progressing innovations across all stages of agri-food value chains today—in digital, genetic, and other spaces—no magic scientific or engineering bullets exist. Few, if any, innovations can adapt and scale effectively without essential supporting policies and institutions. And none can effectively target all four HERS objectives simultaneously. We therefore need a portfolio approach to deliver impact and to ensure balance among objectives. The creative destruction of technological change also inevitably generates both winners and losers, and new technologies inevitably generate both positive and negative spillovers across HERS objectives. Co-creation of bundled approaches is, therefore, essential to enable packages of new technologies and practices to emerge, adapt, and diffuse to scale within and across contexts, and to generate beneficial impacts with limited or no unintended, net adverse consequences.
- ▶ **Reduce the land and water footprint of food:** Meeting future growth in food demand while reducing AFS land and water use is both necessary and inevitable. We cannot effectively tackle the climate and extinction crises and reduce the risk of zoonosis-driven pandemics without reducing AFS demands on land and oceans. Decouple food demand growth from the land and oceans is perhaps the most essential and challenging transition task we face. That process must be actively and cooperatively negotiated among diverse stakeholders.
- ▶ **Commit to co-creation with shared and verifiable responsibility:** The complex pathways from innovation to scaling to impact necessitate co-creation of locally contextualized socio-technical bundles. Because human agency drives everything, all parties need incentives to act, including explicit sharing of both the responsibility to address emergent challenges and the benefits from innovation. Shared responsibilities must be matched with verifiable key performance metrics, agreed sanctions for transgressions, and safety net protections against losses. Co-designed socio-technical bundles can accelerate human agency to facilitate, rather than obstruct, beneficial innovation and minimize unintended consequences.

- ▶ **Deconcentrate power:** Many components of candidate solutions are well known, but impeded by concentrated economic and political power or by the marginalization of key stakeholders. The powerful can too easily obstruct progress (e.g., via catch-and-kill acquisitions, political lobbying, patent thickets). Reducing market and political power imbalances and broadening participation in innovation dialogues can accelerate innovation. Novel financing of discovery for open-source innovation, reforms of intellectual property regimes, and more robust enforcement of anti-trust laws can accelerate beneficial transitions, as can more concerted government and civil society efforts to facilitate participatory dialogues to foster co-creation of effective solutions.
- ▶ **Mainstream systemic risk management:** The COVID-19 pandemic underscores the rising importance of building effective systemic risk management for AFSs. Most governments already appropriately mandate many forms of individual insurance (automobile, fire, health, etc.) so as to resolve market failures and avert catastrophic spillover effects. We increasingly need analogous approaches—both risk reduction and risk transfer mechanisms—to address low-probability, high-impact events (like pandemics) or a rare combination of events (each with higher individual probabilities) that jointly cause a high-impact event (like the 2007–8 food-price spike).⁷
- ▶ **Develop novel financing mechanisms:** AFS innovations and systemic risk management require massive up-front investment of hundreds of billions of dollars additional resources annually. This is feasible but demands creativity, especially to mobilize private resources beyond public spending and philanthropic investments. The world is awash in investible resources, with historically low interest rates and high equity market valuations. The COVID-19 pandemic has proved that governments can quickly mobilize massive public funding when the stakes are high and solutions are urgently needed. Meanwhile, a growing community of private investors recognize the complementarities between longer-term financial and non-financial outcomes. Novel methods to mobilize the financing necessary for transforming AFSs are rapidly emerging.
- ▶ **Reconfigure public support for AFSs:** Governments play two essential roles: investing in essential public goods and services—including basic science, reliable data, and appropriate, effective regulation—and facilitating dialogue to find cooperative solutions. Far too much current government agri-food spending is misspent, especially the roughly US\$2 billion/day that goes to environmentally harmful farm subsidies that impede necessary innovation and disproportionately benefit better-off landowners, many of whom do not actively farm themselves. Governments must crowd in far greater private investment in AFS transformations by redirecting public resources toward social protection programs, agri-food research, and physical and institutional infrastructure (e.g., universal rural broadband access, extension services, product standards, food safety assurance). Governments also play an essential role convening civil society dialogues to facilitate discovery of, and support for, appropriate socio-technical bundles. Governments likewise must lead in co-developing and endorsing commitment frameworks and complementary indicators and accountability mechanisms to ensure effective implementation of identified cooperative solutions at national, regional, and global scales.

References

- Barrett, Christopher B. In press. Overcoming global food security challenges through science and solidarity. *American Journal of Agricultural Economics*.
- Barrett, Christopher B., Tim G. Benton, Karen A. Cooper, Jessica Fanzo, Rikin Gandhi, Mario Herrero, Steven James, et al. 2020. Bundling innovations to transform agri-food systems. *Nature Sustainability*. In press.
- Fanzo, Jessica et al. 2020. The food systems dashboard is a new tool to inform better food policy. *Nature Food* 1: 243–46. <https://doi.org/10.1038/s43016-020-0077-y>.
- Herrero, Mario et al. 2020. Innovation can accelerate the transition towards a sustainable food system. *Nature Food* 1: 266–72. <https://doi.org/10.1038/s43016-020-0074-1>.
- Mario Herrero, Philip K. Thornton, Daniel Mason-D'Croz, Jeda Palmer, Benjamin L. Bodirsky, Prajal Pradhan, Christopher B. Barrett, et al. In press. Articulating the impact of food systems innovation on the Sustainable Development Goals. *The Lancet Planetary Health*. [https://doi.org/10.1016/S2542-5196\(20\)30277-1](https://doi.org/10.1016/S2542-5196(20)30277-1).



 **Cornell
Atkinson
Center for
Sustainability**

**nature
sustainability**