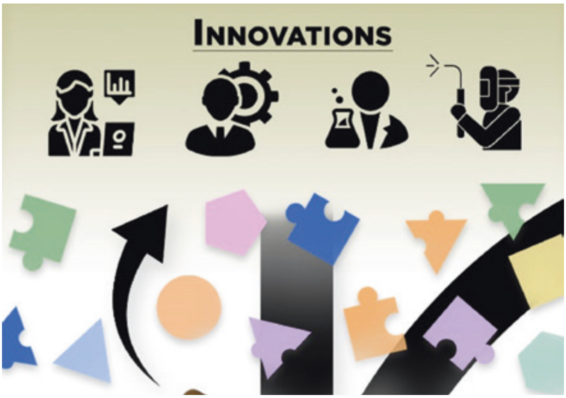
A Profuse Pipeline of Promising Options



Because AFSs are diverse, dynamic, and evolve continuously, they require massive continuous investment to enable ongoing discovery and adaptation merely to prevent backsliding. Major advances in science and engineering are necessary to realize the vision of equitable, inclusive, sustainable AFSs, but they are not sufficient, as human institutions and behaviors fundamentally mediate the translation of scientific discoveries into the sorts of impacts the world needs from its AFSs over the coming decades.

Too many candidate innovations exist for us to enumerate in great detail here.[1] And surely many more innovations not presently (widely) anticipated will

[1] The collaborative online innovations portal we compiled in collaboration with Project Disrupt, goes into much greater detail. One can explore the Innovative Food System Solution portal at https://ifssportal.nutritionconnect.org/.

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Fig. 1 Promising emergent technologies span the AVC (Adapted from Herrero et al. 2020)

emerge serendipitously or strategically in the years ahead. We know, however, that a tremendous range of options exist, spanning the full range of AVCs, from input suppliers, through retailers and food service firms (Herrero et al. 2020). Figure 1 shows that amongst the domains of cellular and digital agriculture, food processing and safety, health, and resource use efficiency, many potentially disruptive technologies span the whole AVC. Digital innovations are especially cross-cutting and numerous. From applications of molecular printing, artificial intelligence, robotics, and the Internet of Things, all the way to biodegradable coatings, new drying methods, personalized food, and the circular economy, all could have meaningful impacts through AVCs. The likely impacts and suitability of any of these inevitably vary among contexts. We take comfort in knowing that **an ever-growing pipeline of innovations could be applied in different combinations to solve particular local problems**. This diversity of innovations already under development or in various stages of adaptation and diffusion demonstrates **that multiple entry points exist to transform AFSs** (Box 1: Prioritizing Interventions).

Scientific breakthroughs generally take a significant time to incubate and evolve into more than prototypes for wider application. For example, variants of controlled environment agriculture, 3D printing of foods using AVC waste materials, and drones have each been under development for decades already. Private R&D investments typically take 5–15 years to generate discernible payoffs and public and philanthropic R&D funding, which is typically targeted at more basic scientific questions, averages 15–25 years to peak return (Chavas et al. 1997).

Nevertheless, the pipeline is healthy and ever expanding. The innovation pipeline is also increasingly well supported by private venture capital that finances an entrepreneurial ecosystem of start-up companies in the agri-food space, perhaps especially for digital agri-food technologies (Graff et al. 2020).

The innovations we studied exhibit a wide range of technological readiness, from innovations already being implemented in multiple locations and sub-sectors to ones that remain targets for basic science research (Fig. 2). A portfolio approach is necessary when thinking about the array of options. Some innovations could have very specific niches, others could be implemented in large domains. Some could have small impacts, others very large ones, as well as a variety of costs and time for implementation. Virtually all will require some—but differing types—of adaptation to suit specific AFS contexts.

Note, too, that **the most promising innovations are not solely, or even primarily, scientific breakthroughs or engineering advances**. Many key "change accelerators"—to use Herrero et al.'s (2020) term—will be sociocultural, policy, or institutional innovations because "transformation is also a deeply political process with winners and losers, which involves choices, consensus as well as compromise about new directions and pathways. Powerful players within agri-food systems have strong incentives to maintain the status quo and their current markets share" (Herrero et al. 2020, p. 267). At the same time, lucrative opportunities exist for those players that choose to help lead AFS transformation, aligning their purpose (and fortunes) to broader societal interests. Some novel organizational forms (e.g., B corporations) directly embrace such opportunities, but even some that follow more traditional organizational forms (e.g., publicly-traded, multinational corporations) are exhibiting real leadership with the expectation that this will bring both social and financial reward.

Significant differences of perspectives exist among experts concerning the potential and desirability of scientific/technological innovations now emergent. In the process of creative destruction of innovation, inevitably some people see progress, while others justifiably worry about prospective harms. There are sure to be unrealized aspirations, unanticipated consequences, predictable problems, and unforeseen obstacles, just as there will be major breakthroughs, some of them scientific, some of them sociocultural or political. Pluralism, intellectual curiosity, and healthy skepticism are paramount in advancing beneficial innovation. Innovation within AVCs is therefore far more than merely a scientific or commercial or technological matter. **Innovation is a sociopolitical phenomenon requiring ongoing consultation and monitoring** if we are to navigate successfully towards the SDGs and the longer-run design objectives of AVCs that promote healthy diets, equitable and inclusive livelihoods, environmental and climate sustainability, and resilience to shocks and stressors.

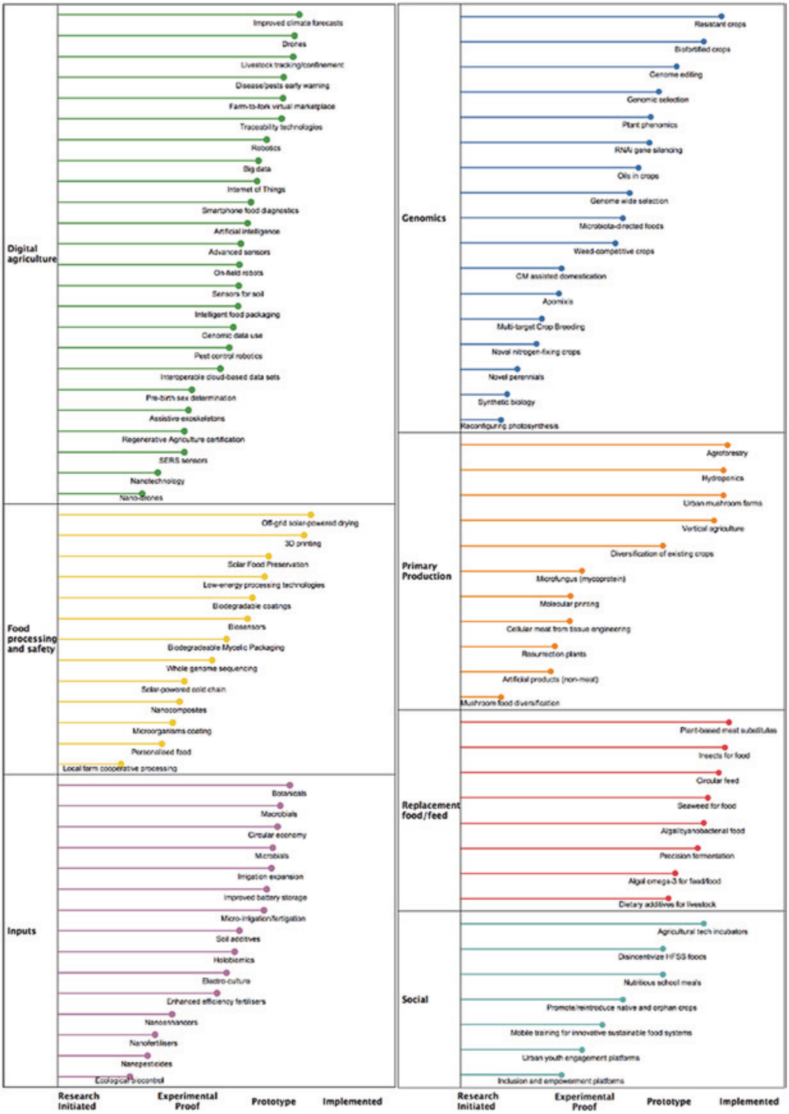

Fig. 2 Technological readiness of future agri-food systems technologies (Adapted and expanded from Herrero et al. 2020)

Given these various pressures confronting AFSs now and in the future, what AVC innovations are most likely to induce healthier diets; more sustainable and resilient production, processing, and distribution systems; and most equitable and inclusive livelihoods? Our panel identified scores of options that appear especially promising in different contexts, in distinct AVC segments, and at different time horizons. We start with four cross-cutting innovation spaces—digital, finance, social protection, and civic engagement—before moving to innovations more anchored in specific AVC stages from farm- and fisheries-based primary production through supply chain intermediaries (e.g., manufacturers, processors, and retailers), to consumer-level health and nutrition innovations. Because of the deep heterogeneity among AFSs and the considerable uncertainty around expected impacts—especially among innovations in the early stages of technological readiness—we make no attempt to rank among these. Moreover, we do not claim to offer a comprehensive listing, given the rapid pace of new discovery in the agri-food space. The sheer volume of promising innovations illustrates, however, that technological options are abundant. The key constraints relate to adapting and scaling innovations to achieve intended impacts, satisfactorily addressing unintended impacts, and setting the right incentives for beneficial innovations to emerge at sufficient pace and scale to transition AFSs towards HERS outcomes while we have time to skirt calamity.

Box 1: Prioritizing interventions for climate-smart agri-food systems*

Technologies will have different impacts on the attainment of different AFS-related SDGs. This is crucial, as different countries—or regions within countries—have achieved different levels of progress towards the different goals. Different countries might, therefore, preferentially focus on making more progress on some goals than others.

As an example from a climate-smart lens, a Delphi panel of experienced agricultural, food, and global change scientists from around the world ranked the technology list from Herrero et al. (2020) on readiness, adoption potential, and potential impact. Several technologies seem to balance readiness, adoption potential, and impacts. The top ten ranked innovations include four technologies relating to replacement food and feed for humans, livestock, and fish: plant-based substitutes, insects, microalgae and cyanobacteria, and seaweed. Driven in large part by concerns about the harmful net environmental impacts of the livestock sub-sector and how income and population growth might magnify that damage, many promising efforts are underway attempting either to meet the growing demand for animal products by providing alternative protein sources that do not rely on livestock or to reduce livestock's impacts on land via animal nutrient sources alternative to traditional feed crops.

Other top-ten technologies include improved climate forecasts and pest/disease early warning that rely on digital advances; circular economy approaches for reusing, recycling, and repurposing waste resources to boost food production while creating new local business opportunities; and vertical farming in confined spaces with no soil or natural light, another way to decouple food production from the land.

*This box draws on material from Herrero et al. (2021).

Digital Innovations

The ecosystem of digital agriculture has exploded in recent years, with the emergence of myriad agri-tech and downstream ventures across the Global South and North. The broader digital ecosystem can be envisaged as a "digital agri-stack." The foundation is made up of the macro-level enabling environment—including connectivity, human capital, and critical data infrastructure—functionality that enables system interoperability, and supporting policies. The second layer is the ecosystem of data and content. At farm level this might consist, for example, of soil and water maps; remote sensing weather data from drones, satellites, and other platforms; farmer profiles; data on animal and plant genetics; local market price and plant disease information alerts; and data from a wide range of sensors. Finally, the products and services that make use of these first two layers comprise the top layer. The various tools and applications can include distinct and bundled services spanning agricultural extension, finance, government support programs, and various advisory services. Figure 3 represents this digital agri-stack concept within the specific application domain of small farmers in rural and traditional AFSs. COVID-19 has increased the value of digital linkages in the food system, enabling people to connect to markets and production, and allowing processing and distribution operations to continue, while reducing the human contact rate of conventional approaches.

Digital technologies have penetrated even into rural and traditional contexts with notable speed, with game-changing innovations often coming from LMICs. In large part, this is due to the advancement and ubiquity of a key digital infrastructure component: the mobile phone (increasingly the smartphone) and wireless connectivity (especially as 4G becomes ubiquitous). Mobile phones have enabled people in Africa and South Asia to leapfrog over generations. But there remain significant inequities. Mehrabi et al. (2020) found that 74–80 percent of farms of larger than 200 hectares had high-speed 3G or 4G connectivity com-

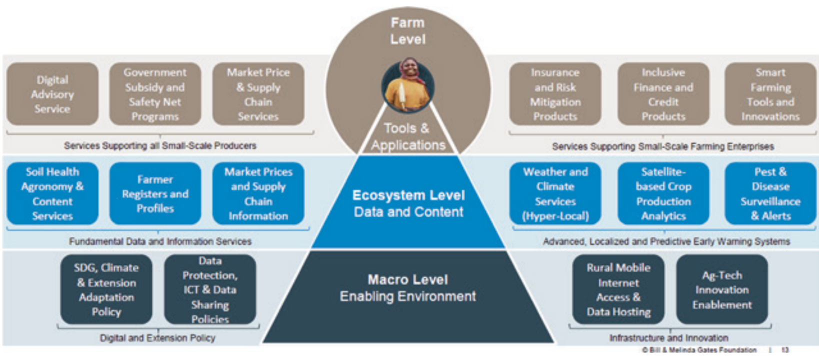

Fig. 3 The digital agri-stack (*Source* Bill and Melinda Gates Foundation, Digital Farmer Services Strategy)

pared to just 24–37 percent of farmers cultivating less than one hectare. Farms with the lowest yields and where farmers face the most climate-related shocks and food insecurity had even less digital connectivity. Data costs in Africa remain high with less than 40 percent of farming households having access to the Internet.

At the same time, digital technologies like mobile banking (e.g., mPESA in Kenya), satellite-based risk management tools (e.g., index-based livestock insurance in Ethiopia and Kenya: https://www.drylandinnovations.com/), interactive agricultural extension (e.g., Digital Green: https://www.digitalgreen.org/), and equipment sharing apps (e.g., Hello Tractor in Nigeria: https://hellotractor.com/) obviate market failures that previously constrained poor, rural populations. These digital solutions typically augment existing in-person networks, like Digital Green's partnership with government extension agents and Hello Tractor's engagement with local entrepreneurs. Those local service providers are essential; digital providers can extend their reach but not compensate for their absence or inefficiencies (Jensen and Barrett 2016). Service availability gaps thereby limit the gains to closing the digital divide.

High-speed data connectivity and smartphones in even the most remote rural communities have nonetheless served as key catalysts for new investments of capital and talent into AFSs. Affordable data pricing and design features that enable neophyte accessibility (e.g., voice recognition) are other key elements of the stack that enable the full range of stakeholders to take advantage of digital advances. Policies and regulations are also needed to create and protect trust and allow the system to continue growing and evolving. Key to this is establishing and enforcing standards that protect data privacy.

The enabling environment of connectivity and confidence facilitates the development and exploitation of critical datasets that then empower the performance of many apps. Some data is collected from users, raising issues of the rights associated with data suppliers and aggregators. Other data can be collected using spectral methods at various scales, including remote sensing from satellites, more locally from drones, and by end users or agents with hand-held devices. Remotely sensed data are increasingly available at ever higher resolution, tagged with metadata to enable their utilization. Analysis of spectral data by machine learning enables

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inferences that can provide users with useful information, such as rapid and low-cost estimates of key indicators of crop identity and health. Though some of these tools are expensive for small-scale producers today, their costs are reducing quickly and the increasing interoperability of sensors, data sets, and cloud-based computational tools enables the sorts of productivity-sustainability synergies that were originally envisioned from—but never fully delivered by—precision agriculture technologies introduced into industrialized AFSs starting in the 1990s (Basso and Antle 2020). The African Cassava Agronomy Initiative (http://acai-project.org/), for example, has brought together data systems, digital interfaces, and analytics to support farmers across a range of channels from mobile apps to paper.

Farmers need such hybrid apps to access reliable, accessible data on soil and weather, for instance. Also, spatially explicit datasets combined with machine learning, for example, can be used to make inferences that are useful to farmers to guide decisions on planting and crop management. Critical datasets for a healthy food system go beyond that to include data that inform actors and actions that manage food quality and safety; track and tap labor markets; provide credit and insurance markets; map nutritional status; monitor sources of pollution, etc. Data pipelines need to not only source raw data, but crucially, to analyze and transform it so that it can be interpreted and acted upon. These require investment to maintain but benefit everyone, including the private sector.

Important innovation is taking place in areas that are critical to farmer livelihoods, including farm advisory services, digitally linking market actors more efficiently, and supporting more efficient product aggregation among farmers. Some extension-based apps enable more precise, efficient, and effective use of seeds and fertilizers, while others provide disease diagnostic services for animals, plants, and people (e.g., PlantWise, https://www.plantwise.org/). Other applications support peer-to-peer (P2P) learning networks supporting entrepreneurs and other service providers who serve as intermediaries in the technical space. Digital capacities can link producers into farmer research networks that collectively build the evidence base (Nelson et al. 2019). Innovative Farmers (https://www.innovativefarmers.org/), for example, is a P2P innovation network that facilitates the building of farmer field groups that have a common challenge to address. Each group is paired with a trained researcher, who guides the members through experimental design and evaluation (e.g., evaluating non-pesticide pest control when neonicotinoids were banned in the EU).

Apps also link farmers, intermediaries, and markets, letting farmers understand and navigate pricing, and enabling farmers and intermediaries to more efficiently aggregate products. This has ignited demand for new infrastructure, like digitally enabled warehouses for logistics providers (e.g., Arya, https://aryacma.co.in, which operates over 1.6 million metric tons of digitally enabled agricultural commodity storage across rural India).

Digital technologies are also helping consumers trace the origins of the foods they consume, stimulating new potential behaviors in the marketplace, as consumers discover an array of innovative products and producers. In India, Stellapps (http://www.stellapps.com) is developing a digital layer traversing the country's massive dairy industry, providing dairy cooperatives and private dairy processors full transparency across the supply chain. Blockchain technology can enhance the visibility of producers, and farm-to-fork virtual marketplaces can further enhance traceability. For example, FishCoin (www.fishcoin.co) is supporting and rewarding supply chain actors who share data that enable full traceability across complex global supply chains.

Digital technology is also simply making it easier for consumers and manufacturers to access what they want, which is increasingly a more direct connection to farms and farmers. In Nigeria, Agriple (www.agriple.com) is connecting farmers with buyers to improve transparency, efficiency, and waste reduction. In China, ecommerce platform Pinduoduo (http://en.pinduoduo.com) has helped more farmers sell online as they turn ecommerce into a social experience that helps consumers learn about farming practices and get group discounts. In India, Ninjacart (http://ninjacart.com) is disintermediating fresh produce value chains, linking farmers directly with shopkeepers and consumers. Similar efforts are also underway across the online grocery sector in India, with direct farmer sourcing for fruits and vegetables initiated by multiple players vying for dominance, including BigBasket, Amazon, and Zomato. Such digital products and services can reduce scale advantages, broadening access to certification processes and high-return markets, leveling playing fields for smaller farms and downstream AVC enterprises, and facilitating more direct P2P and business-to-consumer exchange so as to reduce concentrated power in AVCs. These initiatives have scaled with the liberalization of telecommunications and agricultural policies, and have also piggybacked on government investments in roads, storage, and logistics services.

In industrialized and consolidated AFSs, the public sector publishes key data such as weather and public goods. These data can play an important role in policy design and implementation (Capalbo et al. 2017). Private sector digital tools and technologies have built upon those data and are changing how crops are planted, monitored, harvested, and consumed. The agritech startup ecosystem has driven much of this change, with large agribusinesses acquiring some of the most successful new ventures to ensure their traditional business models are not left behind. Notably, Monsanto (now Bayer) acquired The Climate Corporation (http://climate.com) in 2013, providing them with a strong digital backbone and products like Climate FieldView, which delivers field-level insights to farmers. In 2017, DuPont (now Corteva) acquired Granular (https://granular.ag) to ensure they, likewise, would have farm management software and precision agriculture solutions to provide their farmer customers. The same year also saw John Deere acquire Blue River Technology (http://www.bluerivertechnology.com), a robotics startup that had developed "see-and-spray" technologies for weed control, leveraging computer vision and artificial intelligence.

More recently, hyper-funded farmer platforms like Farmers Business Network (https://www.fbn.com) and Indigo (https://www.indigoag.com) have sought to redesign more fundamental aspects of the agricultural economy in the modern advanced, industrialized AFS. Farmers Business Network is trying to break the dominance of the Big 4 (Bayer, BASF, Corteva, and Syngenta) in seeds and crop protection chemicals, helping farmers to make data-driven decisions regarding inputs, while also providing access to crop insurance, commodity brokerage, financing, and other services. Indigo, on the other hand, started out developing innovative microbial products but is now focusing more on building a post-harvest marketplace for grain sales, commodity transportation solutions, and a carbon sequestration platform. Both players are well capitalized, having raised a total of US$571 million and US$1.17 billion from investors (including US$250 million and US$360 million in August 2020 alone) for Farmers Business Network and Indigo, respectively.

Other notable innovations enjoying accelerating farmer adoption in more industrialized AFSs in recent years include field-based Internet-of-Things systems integrating sensors and agronomic algorithms (e.g., CropX, https://www.cropx.com); precision agriculture platforms to optimize farm equipment (e.g., Solinftec, https://solinftec.com); and farm robotics, where startups have initially focused on weeding use cases (e.g., Naio Technologies, https://www.naio-technologies.com, and ecoRobotix, www.ecorobotix.com) but are now beginning to tackle harvesting (e.g., Advanced Farm Technologies, https://www.advanced.farm, as well as Root AI, https://www.root-ai.com), and dairy parlor management.

Further downstream, we find agritech startups working to improve post-harvest supply chains, often focused on creating better market linkages between farmers and buyers. In the American heartland, Bushel (https://bushelpowered.com) has set out to "facilitate clear and simple business

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between grain companies and growers" through a mobile application. In California (and other horticultural regions), Full Harvest (https://www.fullharvest.com) has created a digital business-to-business (B2B) marketplace to help growers sell ugly and surplus fresh produce to food processors and other potential buyers. Imperfect Foods (https://www.imperfectfoods.com) has a similar mission of fighting food waste but works across grocery categories and delivers "rescued foods" directly to customers' homes. Finally, GrubMarket (https://www.grubmarket.com) has carved a niche for itself as a farm-sourced version of Instacart, offering food products at wholesale prices to both B2B clients and consumers.

Even with an enabling environment (connectivity and data) and a range of apps, the performance of the digital agristack can underperform if the ecosystem of data and insights becomes fragmented. The adoption of a common technology platform can help AFS actors converge and continue to enhance system performance. An *enabling* technology platform for any ecosystem has several components. For instance, different tools help us find data (*data discovery*), translate it into a common form (*data transformation*) and make it easy to share (*data transfer*). These services are neutral to content but required to make it easy for individuals and organizations to safely exchange or combine data. FarmStack, currently under development by Digital Green, is developing a decentralized architecture comprised of P2P connectors specifically addressing this last service. P2P connectors ease the data exchange process between partners. Of course, as data are sensitive and valuable assets, data owners want to protect them, and farmers need to have the ability to monetize their own farm and farmer profile information which other third parties can leverage to build their own applications. Therefore, FarmStack is also developing and codifying usage policies that will ease and automate this over time, accelerating the exchange of public and proprietary data to drive collective impact as well as inform policy-makers and research.

One example of a new data layer that could foster the emergence of innovative new products and services throughout AVCs is the Rockefeller Foundation-supported Periodic Table of Food Initiative (PTFI), a global effort to create a distributed network of labs using standardized methods to populate and continuously update a database of the full biochemical composition and function of food using the latest mass spectrometry technologies and bioinformatics. The current scientific understanding of food covers, at most, 150 of foods' biochemical components, typically summarized as sample averages in conventional nutrient composition databases. A food system that supports human and planetary health, however, requires rigorously collated data covering the full range of the tens of thousands of biochemical molecules in food that mediate the relationships between food, diet, health, nutrition, and the environment. PTFI can enable interoperability of data and democratize the analysis of food with the development of low-cost kits, standards, methods, cloud-based analytical tools, and a self-sustaining, broadly accessible database—the Periodic Table of Food—that will include the quantitative and qualitative analysis of foods. These data can better equip AVC actors to personalize diets and promote health for individuals based on specific needs, development stage, age, health status, and other factors, as well as improve agricultural systems for increased environmental sustainability and resilience to various biotic and abiotic shocks.

An interoperable platform of services can speed up the potential for new insights, services, and products. As already mentioned, a broad range of apps have already emerged, from physical products (e.g., robotics and smart sensors) to human networks (e.g., crowdsourcing production insights or plant disease surveillance) to conceptual (e.g., a predictive analytics app that helps farmers decide what to plant based on likely weather and market conditions). Future applications will also solve problems where we cannot yet see clear connections at the intersection of agriculture and health, financial services, and human rights, easily integrating data and producing unforeseen relationships and solutions. The barriers to more novel digital innovations in AFS primarily arise from consumer and farmer acceptance. For example, a price premium has emerged for older-model farm machinery in secondhand markets in the US as farmers seek simpler equipment that is cheaper and easier to maintain and to safeguard their privacy from equipment dealers and service providers.

Unintended consequences will almost surely arise from digital innovations, as with any new technologies. For example, digital marketplaces that help farmers sell ugly or surplus produce may deprive food banks and pantries of an important source of healthy foods to provide their patrons, or they could siphon demand from other growers, thereby depressing prices small farmers receive. Individual-specific data can enable retail or food-service marketing campaigns more effectively targeted to manipulate consumers' weaknesses or allow agro-input dealers to bundle inputs and services to extract greater profit by exploiting detailed knowledge of farmers' behaviors. If too many digital innovations get locked up in patents, it could slow advances and make IP-protected new technologies unaffordable for lower-income subpopulations. And high-tech solutions can never fully overcome natural inferential limits to generating precise, field- or farm-level information on soils and other key variables that influence farmer decision-making (Schut and Giller 2020).

Digital innovations is one space not struggling to secure adequate private investment right now. Access to adequate finance does not, however, characterize most of the AFS innovation space.

Innovative Financing

Product and process innovation inevitably requires significant up-front investment. CERES2030 (https://ceres2030.org/) recently estimated that donors need to more than double their annual contributions targeted towards food security and nutrition objectives, increasing them by an additional US$14 billion to 2030. In addition, developing-country governments will need to commit a further US$19 billion each year, just to meet three of the five targets under SDG 2 (zero hunger), with two-thirds of this additional public spending focused on Africa (Laborde et al. 2020). This assumes that government and donor spending will crowd-in an extra US$52 billion in private investment annually. This US$85 billion/year estimate is almost surely a lower bound on the scale of financing needed to transition AFSs in the developing world to meet the broader HERS objectives—not just three of five targets under SDG 2 to 2030—much less the financing needed globally.

Inducing sufficient investment in AFS innovation will require innovations in finance. The resources exist. Global assets under management at the end of 2019 stood at US$89 trillion (Heredia et al. 2020). And with interest rates at historic lows, investors actively seek promising new investment opportunities. But most capital is allocated by private investors, who presently lack incentives to address environmental or public health externalities, or to attend to needs in low income countries where limited purchasing power and weak institutional and governance frameworks depress commercial potential. To effectively exploit food-demand growth over the coming generation—especially in sub-Saharan Africa where the bulk of additional demand will occur—AVC innovations must address pervasive climate, environmental, health, and social justice spillovers in order to ensure long-term, sustainable returns. Some recent innovations and a growing pool of capital searching for aligned opportunities show promise for helping foster accelerated AFS R&D finance and for growing investment in AVC innovators committed to advancing HERS-consistent AVC transformation.

Historically, much critical basic science funding came from governments and philanthropies. That was true of the US agricultural revolution of the 1930s–1950s and of the Green Revolution in Asia and Latin America in the 1960s–1980s. But outside of a few middle-income countries (Brazil, China, and

India) that have invested heavily in agricultural R&D due to the strategic importance of the sector to their economies, public investment in agri-food R&D slowed dramatically over the 1990s and 2000s (Pardey et al. 2016). Some of this decline was due to complacency in the wake of Green Revolution successes, and there has been renewed interest on the part of some donors since the 2008–2012 global food-price spikes. Most recently, in 2019, multiple bilateral and foundation donors committed to a major expansion of funding for the CGIAR—the main network of multinational agricultural research institutions—as part of structural reforms to that global agricultural research organization. But public and philanthropic investment remains woefully insufficient to meet the yawning innovation needs of AVCs.

Reallocation of current government farm subsidies offer an obvious source for public finance for AFS innovations. Subsidy programs in most Organization for Economic Cooperation and Development (OECD) countries and in China largely impede, rather than advance, necessary innovations towards more sustainable, resilient, inclusive, and equitable AFSs (OECD 2020; Searchinger et al. 2020). **Only one-eighth of total government support of agriculture presently goes to R&D, inspection and control systems, and rural infrastructure—the things that promote beneficial innovation**—as compared to three-quarters provided as financial transfers to individual producers, mostly in a distributionally regressive manner that reinforces inequality (OECD 2020). One centerpiece of a strategy to mobilize private finance involves fixing the distorted incentives created by government agriculture subsidies that implicitly promote investment in practices and products that generate serious environmental and health spillovers. Agricultural subsidy reform is politically fraught everywhere but essential to get market signals right to induce investors to divest from unsustainable and unhealthy enterprises. The high-level Financing Nature report emphasizes “harmful subsidy reform” as its top recommendation for mobilizing finance to stem the looming biodiversity/extinction crisis (Deutz et al. 2020).

The largest and growing share of agri-food R&D investment comes from private firms (Pardey et al. 2016) (e.g., by machinery, fertilizer, and agrochemical manufacturers; seed companies; food processors and manufacturers; retailers; and food or third-party logistics enterprises). Their commercial objectives can dovetail nicely with broader societal interests in circumstances where prospective beneficiaries are able, and willing, to pay for improved products and processes, and where effective regulatory oversight or appropriate tax policies limit any negative externalities that arise from the innovation. Just as private agri-food R&D has increasingly dominated the innovation landscape over the past generation (Pardey et al. 2016), so has public awareness that modern AVC innovations commonly lead to uncorrected climate, environmental, health, and social justice externalities and fail to address the needs of the poor, who rarely present a lucrative market to investors. Simply mobilizing more capital under current financial market designs seems an unlikely path to success.

Innovation in private investment will be necessary to advance beneficial AVC innovation and finance the widespread adoption of innovations. One modest, but important, development is the rise of institutional investors with a longer-term view on returns. Whether driven by social and environmental concerns, rising concern about the downside risk of stranded assets, diminishing returns to more conventional assets, or some other motive, private investors, pensions, and others with decades-long returns horizons are increasingly investing in regenerative agriculture, sustainable forestry and fisheries, green bonds, etc. For example, as of 2019 there was more than US$320 billion under management in assets focused on regenerative agriculture in the US alone (Electris et al. 2019). Equally exciting is the emergence of a robust and growing conservation finance movement, mobilized by groups such as the Coalition for Private Investment in Conservation. Conservation finance is developing new financial instruments that are attracting private investment in financially attractive conservation investments (Deutz et al. 2020).

Across the globe the momentum is building around Environment, Social, and Governance (ESG) investing, which offers a set of recognized criteria that value-based investors can use to deploy capital for sustainable, long-term financial gains that align their principles with those of their shareholders (Boffo and Patalano 2020). While ESG rating methodologies and standards continue to be refined, the broader impact-investing market—of which ESG is only a part—has risen sharply over the last decade, now encompassing at least US$715 billion in assets under management (GIIN 2020). The impact-investing market is widely expected to grow further as evidence mounts on the positive relationship between ESG investment and corporate financial performance (Friede et al. 2015). Many ESG funds are allocated by specialized asset managers (i.e., Paris-based Livelihoods Funds) that have emerged to pool resources from private companies—including massive AVC corporations—for investments in sustainable agriculture in smallholder farming communities around the world.

While shifting investor preferences create new opportunities and unlock additional capital, thus far this remains a modest share—ten percent or less—of global private assets under management and a fraction of the resources required to trigger necessary AVC transformation. The first challenge to overcome is a geographic one. **Although international financial markets increasingly integrate economies around the globe, investment capital remains anchored to**

high-income countries by home country bias. Agroecosystems exhibit huge heterogeneity, however. Place-specific R&D is therefore essential as are localized AVC innovators and enterprises to drive adoption of HERS products and services at scale.

ALTHOUGH INTERNATIONAL FINANCIAL MARKETS INCREASINGLY INTEGRATE ECONOMIES AROUND THE GLOBE, INVESTMENT CAPITAL REMAINS ANCHORED TO HIGH-INCOME COUNTRIES BY HOME COUNTRY BIAS.

Given that most growth in food demand will take place in Africa (Box 1 in Chapter 3)—where agri-food productivity lags and environmental, healthy diet, equity, and inclusion concerns are legion—that is the continent most in need of AVC investment capital. Governments and international donors can help, but catalyzing private investment is essential and currently woefully insufficient. The simple reason is that African markets are widely perceived as less lucrative and higher risk than are high-income markets, so private investment flows lag far behind where they need to be. The bulk of private agricultural R&D investment worldwide is undertaken by a small number of massive firms; less than two dozen firms accounted for more than 70 percent of global private agricultural R&D from 1990 to 2014 (Fuglie 2016). Private agricultural R&D in developing countries accounts for only two percent of global R&D investment in the sector globally (Fuglie 2016).

We can only increase private investment in agri-food innovation in developing countries by adjusting investor incentives and designing enabling environments to promote and direct investor appetite. Innovative ideas with considerable potential are already being successfully employed. For example, the growing Green, Social, and Sustainability Bonds movement seeks to coordinate major international financial institutions and other significant players in global financial markets to support a framework intended to catalyze ESG investments. The International Capital Market Association (ICMA) has been mandated to develop a set of guidelines and principles for bond market issuers, to ensure that participants deploy and manage raised capital to facilitate and support green, socially-conscious, and sustainable investing.[2]

[2] A systematic mapping of Green, Social and Sustainability Bonds financing to which ICMA seeks to contribute is available at https://www.icmagroup.org/green-social-and-sustainability-bonds/.

Capital markets have already responded positively. Moody's projects US$400 billion in global green bond issues in 2020,[3] continuing a sharp growth trend of approximate market doubling every 2–3 years. This is likely to trigger additional inflows into underserved markets, such as Africa. A landmark agreement signed in September 2019 between Japan's Government Pension Investment Fund—the world's largest—and the African Development Bank (AfDB), supporting inclusive and sustainable growth in Africa, led to an oversubscribed US$3 billion AfDB Social Bond that was the largest USD denominated social bond transaction in capital markets when issued in March 2020.

A bottleneck to unleashing the full potential of sustainable financing remains the formalization of coherent, transparent, and standardized definitions of, and ratings for, various classes of projects. Generalized endorsement of taxonomies that can underpin regulations and generate the capacities, instruments, and reporting frameworks to appropriately steer capital flows are important. At the global level, the International Platform on Sustainable Finance (IPSF)—whose growing membership currently represents roughly half of the world's population and half of global GDP, and which also emits half of the planet's GHGs—is promoting information disclosure standards, policy frameworks, and a global governance architecture consistent with stimulating private investment and steering capital towards ESG objectives (IPSF 2020). This complements the Harmonized Framework for Impact Reporting for ESG investments endorsed by eleven leading international financial institutions.[4] In general, ESG instruments—and particularly the "Governance" component—are expected to have a significant, positive stimulus impact on private financing for emerging and developing economies where risks arising from uncertain information quality, unclear institutional frameworks, and weak governance have limited investment to date.

Even as these regulatory frameworks develop within the international public arena to promote private sector investment, businesses are also developing their own certification processes to signal their values and position themselves to attract both aligned investors and consumers. The emergence of certified B corporations (B corps)—a pro-social business form that puts environmental and social performance on par with financial performance—has shown promise as a way to internalize the true social costs and benefits of an enterprise's activities.

[3] https://www.moodys.com/research/Moodys-Green-social-and-sustainability-bond-issuance-to-jump-24--PBC_1212910.

[4] Details available at https://www.icmagroup.org/assets/documents/Regulatory/Green-Bonds/Handbook-Harmonized-Framework-for-Impact-Reporting-220520.pdf.

B corps are hybrid enterprises that legally commit to third-party environmental and social audits conducted by B Lab, a US-based non-profit organization. In many ways, B corps epitomize social entrepreneurship. But since their emergence as a distinct organizational form in the 2000s, only about 3,500 companies in 74 countries have adopted this form—including significant ones in the AVC space, such as Ben & Jerry's, Cabot, Danone North America, and Klean Kanteen—and these have not yet had a major impact on AVC innovation or investment patterns.[5] Greater creativity and innovation remain necessary to mobilize finance for agri-food R&D.

Another class of promising innovations to unlock financing—particularly suited to cutting-edge R&D—comes from advanced market commitments (AMCs), wherein governments or donors guarantee a sufficient scale of remunerative purchases of any innovation that meets pre-specified impact criteria. AMCs aim to induce private investment and ensure subsequent access to the technology by low-income users. AMCs have been used successfully for pneumococcal vaccine (Kremer et al. 2020). Many lessons remain to be learned about AMC design, but the pneumococcal experience thus far is estimated to have resulted in 700,000 lives saved at a highly favorable cost/benefit ratio (Kremer et al. 2020). Other innovation incentives (prizes, contests, etc.) likewise show promise (Wagner 2011) and are currently being implemented in the AgResults prize competitions operated by the World Bank and in the Food System Vision Prize sponsored by the Rockefeller Foundation.

A SIMPLE CHANGE TO PATENT LAWS IN HIGH-INCOME COUNTRIES COULD SIGNIFICANTLY BOOST INCENTIVES TO AGRI-FOOD R&D FOR THE GLOBAL SOUTH.

Another approach is to modify intellectual property rights. Patents offer inventors a government-sanctioned monopoly in a novel and useful discovery for a period of time in exchange for public release of all the technical details necessary to replicate the innovation. Patents' lucrative prospective returns lure large investments. Currently, however, the meager prospective monopoly returns to innovations in orphan crops in low-income countries, simple irrigation technologies suitable for the Global South, or crop drying technologies for small-scale farmers,

[5] Figures as of end-August 2020, per B Lab's web site (https://bcorporation.net/). See Cao et al. (2017) for a history of B corps, and Moroz et al. (2018) for a series of studies on their strategies and impacts.

etc., result in private under-investment in R&D for low-income markets. **A simple change to patent laws in high-income countries could significantly boost incentives to agri-food R&D for the Global South**. The idea is reasonably straightforward (Barrett 2020). In its patent application, an inventor would volunteer to dedicate its patent to the public—that is, forfeit its right to deny licensing to third parties, thereby relinquishing its monopoly supply right—in exchange for an extension of an alternate, existing patent on a non-essential product, meaning one not needed to safeguard life or essential liberties. For example, a firm with a highly profitable patent on treatments for male hair restoration[6] might profitably extend that patent for several years if, and only if, it were to develop a non-toxic means of eradicating a pest like fall armyworm or diseases like East Coast fever or black sigatoka that afflict low-income tropical agroecosystems, for which there is likely little commercial profit but great humanitarian benefit (Barrett 2020). The essence of the idea is to induce investment in socially beneficial innovations by firms that can extract monopoly rents from high-income consumers' demand for luxury products and services[7] but that could not easily recoup investments from the new discovery's primary intended beneficiaries.

The other challenge to mobilizing finance for beneficial innovation surrounds how to monetize spillover effects on the environment and third parties, including future generations. Partly, such concerns motivate public and philanthropic investment. But regulation and tax policy can also reduce the returns on activities that generate negative externalities. Combined with subsidies to those actions that generate positive externalities, the regulation and tax policies together can correct market failures and induce greater pro-social private R&D, as well. Hence the value of taxes on unhealthy highly processed foods and emissions of GHG and other pollutants, and subsidies for on-farm conservation, investment in renewable energy fixed capital, and employment of workers from marginalized subpopulations.

Some HERS objectives can be advanced through regulatory requirements on banks, insurers, and publicly traded corporations to disclose environmental and

[6] One could imagine many such examples of lucrative, nonessential, patent-protected discoveries, including smart phone apps or digital file compression methods, performance-enhancing devices for recreational goods (e.g., skateboards, ski bindings), pet clothing, etc.

[7] The target would be patented product with high income elasticity but low price elasticity of demand—that is, goods demanded mainly by high-income populations that are sufficiently price insensitive such that firms can extract significant monopoly rents.

social impacts of investments as a fiduciary duty to investors and society. The stronger disclosure frameworks being promoted to induce high standards of ESG performance, and the certification and reporting instruments being established to increase the confidence of impact investors can, likewise, increase the efficiency and targeting of tax and subsidy incentives. When combined, for example, with markets to facilitate emissions trading and improved technologies for monitoring and verifying nutrient fluxes—and enhanced screening, verification, and tracking of investments and innovation impacts facilitated by digital innovation and artificial intelligence—the potential to monetize the provision of environmental services can be a powerful inducement to increase beneficial investment in HERS-consistent R&D and enterprise.

Innovative Social Protection Instruments

Transformation inevitably brings dislocation. **Facilitating inclusive transformation requires effective social protection instruments 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 (Barrett 2013). We witness this today in the rise of nationalist, populist political movements worldwide at a time of significant technological change that has concentrated gains among a privileged few while destabilizing many.

The Nobel Laureate Amartya Sen famously wrote, "Starvation is the characteristic of some people not *having* enough food to eat. It is not the characteristic of there *being* not enough food to eat" (1981, p. 1, emphasis in original). If we are to advance equity, inclusion, and healthy diets objectives, then demand-side innovations must accompany the supply-side ones that usually attract most of the attention in discussion of agri-food systems. Perhaps paramount among these are enhanced coverage and effectiveness of social protection instruments.

Social protection instruments aim to protect individuals from unnecessary human suffering of any sort, including diet-related ill health and extreme poverty. The idea behind social protection is to catch people who fall into hardship and assist them until they are able to sustain themselves again, thereby both preventing descents into poverty traps in which deprivation becomes self-reinforcing and encouraging productive risk-taking by instilling confidence that one will be supported in the event of misfortune (Barrett et al. 2019). Social protection instruments represent the main demand-side innovations essential to AFS transformation.

Social protection programs of various types have expanded dramatically over the past generation or so—and especially during the COVID-19 pandemic

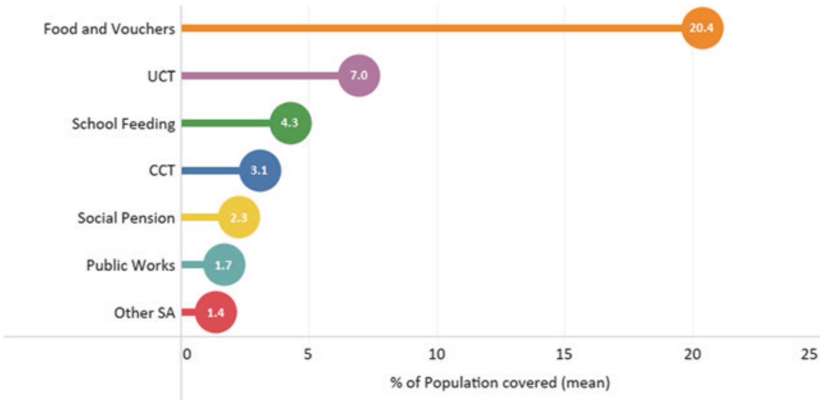

Fig. 4 Social protection program coverage among 108 low- and middle-income countries (*Data source* Alderman et al. 2017) (CCT = conditional cash transfer; SA = social assistance; UCT = unconditional cash transfer)

(Gentilini et al. 2020a)—with different purposes and impacts. But as shown in Fig. 4, food assistance programs remain the dominant mode in LMICs, covering at least 20 percent of the population—1.5 billion people—in 108 countries, more than double the total covered by conditional and unconditional cash transfers and nearly five times the population covered by school feeding programs (Alderman et al. 2017). Bastagli et al. (2016) found that at least 130 LMICs have at least one unconditional cash transfer, and about 63 have at least one conditional cash transfer. The International Labour Organization, nonetheless, estimates that only 45 percent of the global population is effectively covered by at least one social protection benefit and that developing countries alone need to invest an extra US$1.2 trillion to close their annual social protection financing gap (ILO 2020).

Myriad forms of social protection exist. Some provide a substitute for income and may include cash and in-kind transfer programs to directly boost incomes through policies (e.g. universal basic income, employment guarantee schemes, labor-intensive public works programs). Others reduce the cost of essential goods (e.g., food subsidies, vouchers, food stamps). Still others provide mechanisms to ensure access to essential public services (e.g., school scholarships, fee waivers for health care services, universal rural broadband access). Some of the most widespread and politically popular social protection programs are food assistance programs that aim to directly enhance food access (Alderman et al. 2017)—for example, through the provision of public works employment paid in food, increased purchasing power (through the provision of food stamps, coupons, or vouchers), and food-based relief interventions (through the direct provision of food to households or individuals). Some are carefully targeted in an attempt to focus coverage on specific subpopulations only (e.g., girls, orphans, and vulnerable children; the elderly; refugees; school children). Some programs only confer benefits conditional on participants engaging in specific, mandated behaviors (e.g., keeping children enrolled in school, contributing labor effort to public works programs, etc.)

Figure 5 depicts how different social protection programs fit together, depending on the targeting, mode, and conditionality of transfer. Many countries operate multiple such programs (e.g., the public distribution system and the national rural employment guarantee scheme in India, two pillars of that nation's broader welfare system) as illustrated in Fig. 5.

Given the variety of social protection programs already in use across most countries in the world, why is innovation needed in this space? Three main issues need attention. Each of these involves some combination of technical advances based on science and engineering. Mainly, however, innovations in social protection require social support and political will to invest in equitable, inclusive outcomes. **Particular attention is needed to overcome longstanding, systemic discriminatory access** on the basis of ethnicity, gender, race, religion, etc., that exists—but manifests differently—in virtually all countries. Active efforts are commonly needed to address underlying inequities through targeting and differentiation in benefits.

First, abundant evidence suggests that food-related social protection programs improve beneficiaries' lives, particularly for households that suffer from a food security shock (Behrman and Hoddinott 2005; Behrman and Skoufias 2006; Alderman et al. 2017; Hidrobo et al. 2018). But demonstrated food-related gains have been concentrated mainly on caloric acquisition and food expenditures (Hidrobo et al. 2018). The impacts on dietary diversity and quality, perhaps especially among children, remains mixed (de Groot et al. 2017). For example, a meta-analysis evaluating 15 different safety-net programs found that the impacts on child growth were insignificant overall, but at the same time, demonstrated impacts on growth in Brazil, Colombia, Ecuador, Mexico, South Africa, and Sri Lanka (Manley et al. 2012; de Groot et al. 2017).

PARTICULAR ATTENTION IS NEEDED TO OVERCOME LONGSTANDING, SYSTEMIC DISCRIMINATORY ACCESS ON THE BASIS OF ETHNICITY, GENDER, RACE, RELIGION, ETC., THAT EXISTS—BUT MANIFESTS DIFFERENTLY—IN VIRTUALLY ALL COUNTRIES.

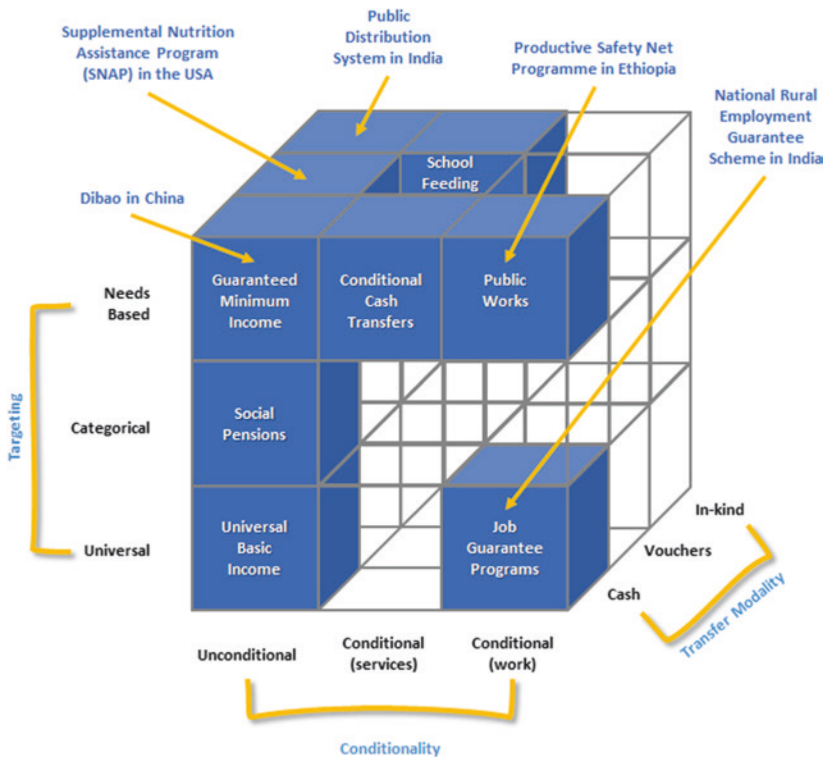

Fig. 5 How different social protection measures fit together (Adapted from Gentilini et al. 2020b)

Conditional cash transfer and food transfer or subsidy programs in Mexico, Egypt, and the US improve elements of diet quality, food insecurity, poverty, and undernutrition outcomes (Hawkes et al. 2020). Indeed, some social protection programs inadvertently increase diet-related risk of obesity and non-communicable diseases (Kronebusch and Damon 2019; Hawkes et al. 2020). So the first direction of necessary innovation is to redesign food-related social protection programs around healthy diets objectives, rather than merely avoiding hunger and undernourishment. This could occur through improved food reformulation, food assistance programs more restricted to nutrient-rich (rather than calorie-dense) foods, or other methods. Mainly, it requires political will and a change in mindset.

Second, although social protection programs' coverage appears widespread, huge numbers of people slip through the safety nets, especially marginalized populations in remote areas. Errors of inappropriate exclusion can be reduced through several directions of innovations. First, as climate, disease, trade, and other risks loom larger, we need improved early-warning systems to trigger prompt expansion of social protection programs to meet changing and growing needs. Some of this can be accomplished through advances in remotely sensed or crowd-sourced data collection, combined with advanced analytics to generate accurate, near–real time indicators of evolving needs and food supply conditions (Jean et al. 2016; Fanzo et al. 2020; Lobell et al. 2020; Porciello et al. 2020; Yeh et al. 2020).

Systems could be developed to improve the adaptive management of response form—as sometimes households most need cash to meet varied food, health, and other needs, and at other times (e.g., in hyperinflationary environments) in-kind food transfers can provide essential protection against food-price spikes. Continued advances in reliable, low-cost, secure transmission of mobile cash and vouchers can also accelerate response to safeguard healthy diets for vulnerable populations, especially in conflict-affected areas where delivery is costly and dangerous, and rapid response is of greatest humanitarian importance. Finally, diverse social protection programs remain remarkably unintegrated. Digital and other technologies can more effectively network large-scale programs (e.g., those provided by national governments), with more informal, local, and/or private food assistance programs (e.g., through food banks and pantries), automating enrollment and distributing resource demands more effectively.

Third, **the increasing digitization of social protection programs poses real risks to individual privacy and dignity**. Biometric methods can help reduce fraud to ensure prudent use of scarce public resources. But when only marginalized populations are subjected to facial, fingerprint, or other recognition tools, or if it is only beneficiaries whose personal data are made available to private vendors and service providers that may prey on underinformed consumers, programs intended to help the vulnerable can become tools of exploitation, discrimination, and disadvantage.

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. AFSs are both highly complex and evolving very rapidly. Technical innovations too often tend to be "pushed" (i.e., originating from R&D and effective marketing of new discoveries) rather than "pulled" (i.e., from citizens asking for new ways of doing things). And the silo-ed organization of innovation and governance ecosystems too often lead to the emergence of new products and practices developed from a reductionist, rather than a systemic, perspective to meet narrow commercial, political, or scientific aims rather than assessing synergies and tradeoffs more broadly to anticipate whether innovations will likely prove "system positive" in terms of their total impacts through positive and negative feedback pathways. The result is too often unintended, but rather predictable, adverse consequences or unfulfilled promises. The fact that our AFSs are growing ever more complex and, at the same time, the future is becoming more uncertain requires new ways of thinking to achieve "system positivity," and underpinning knowledge becomes increasingly key (though, as discussed below, knowledge—like technology—is usually necessary but rarely sufficient to engender change). As we emphasize further in the next section on socio-technical bundles, institutional innovation in civic engagement seems especially important now: innovations in engagement for AVC actors, both upstream and downstream; for policy development; and for public support (particularly through farm subsidy reform). **We urgently need both technological and institutional advances that counter concentrated commercial and political power**, in order to ensure authentically beneficial and inclusive innovations.

Innovations in upstream AVC actor engagement grow increasingly feasible in a rapidly digitizing and globalizing world. As discussed above, digital innovations are increasingly empowering farmers and food producers to innovate within their own circumstances—to adapt to challenges, adopt new opportunities, and/or harness the wisdom of crowds. Digital technologies increasingly enable connectivity that can facilitate greater inclusion in agri-food innovation and in shared governance, so as to accelerate and broaden impacts. Robust engagement is limited largely by connectivity, which reinforces the need for universal rural broadband.

Just as innovations are needed to network upstream producers (i.e., farmers, fishers, herders, etc.) more effectively, so, too, is broader citizen engagement in AVC governance, a pressing issue. In some senses the world is awash with data, yet the data we need to make informed decisions is often difficult to find. This frequently occurs because data are proprietary, because there is no regulated

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requirement for data transparency, or because data curation services are proprietary or absent. Artificial intelligence has made significant advances in collating, curating, and identifying associative relationships between different data streams but remains an imperfect science. Given advances in sensor and distributed ledger (e.g., blockchain) technologies to verify key details of production, transformation, and distribution processes and to store those data in nonmanipulable forms, it is increasingly feasible for citizens to access—should they so want—detailed data on how the food they consume is produced, transported, and processed, as well as evidence of its safety, the contractual terms of its production and sale, etc. Social media is also driving greater transparency by shining a spotlight on issues of consumer concern (e.g., unfair labor practices, unsustainable or unsafe production processes, etc.). Individual-level accessibility to such data, bringing down the energy and financial costs of its production, are high priorities in order to enhance civic engagement in AFS governance.

Policy is often set and managed by government departments—ministries or public agencies that are highly silo-ed, with little public input, and based on a sectoral or segmented view of the world, one that may not accord with how real-world AFSs function. For example, in the UK, there are 16 departments or agencies involved in the regulation of the AFS and its relationship to agriculture, trade, health, food safety, and the wider economy. Therefore, insufficient efforts are typically made for policy development within a ministerial silo to be assessed holistically.

Innovations in this space include attempting to harvest "the wisdom of the crowd" through citizen assemblies, which take their form by bringing groups of citizens together to discuss issues to aid the navigation of complex policy space, and for more deliberative attempts to develop cross-government policy solutions. One nice example is the UK's National Food Strategy, which aims for a holistic approach to AFSs, seeking system-positive outcomes, rather than outcomes that simply improve farm profitability, reduce food prices, tackle food waste, or attempt to carry out some other narrow goal.

A key area for perhaps riskier and more transformative policy framing would be the use of alternative metrics of national good, beyond national income. The level and/or rate of growth of GDP or national income—typically in inflation-adjusted, per capita terms—are too often regarded as the principal socioeconomic performance index. The deficiencies of GDP and income measures are very well known: they fail to internalize damages to nature or climate; they do not value essential nonmonetized activities (e.g., caregiving) but do value monetized destructive activities (e.g., weapons manufacture and sales); and beyond a low-level production and consumption, measures correlate weakly, if at all, with happiness and life satisfaction measures (Stiglitz et al. 2010). At a societal level, which depends on living on a finite planet, incentivizing consumption growth also drives unsustainability, which increasingly—such as through climate anxiety—is undermining well-being. Innovative ways to measure societal well-being in a more nuanced way than GDP have been developed (e.g., the OECD's Better Life Index [OECD 2018]), and a few countries have begun to use these measures in place of GDP and national income. Improved measures shift discourse in a system-positive direction. These would incentivize a very different innovation environment, as the contribution of diets to planetary health and well-being would require that they not be considered "externalities" to the AFS.

Citizen assemblies might also inform the navigation of complex systems, where trade-offs are rife, and lead to greater clarity as to what positive systemic outcomes citizens really want, rather than relying on simple, unnuanced, and inaccurate proxies like "consumers want cheap food." Lack of clarity presently facilitates special-interest-group capture of vast public agri-food sector subsidies, mostly in forms that distort markets and in a manner that aggravates pre-existing income and wealth inequality because the wealthiest farmers—indeed, often just landowners who do not farm—receive the biggest payments (OECD 2020). **It is hard to believe that present subsidy programs reflect citizen desires as opposed to raw interest group pressures**. With greater clarity around desired systemic outcomes, public money can be more effectively targeted at them. As highlighted by Springmann (2021), changing the subsidy regime can have significant impacts on food availability, price and diets, and dietary illness (e.g. refocusing subsidies from calorie-dense starchy grains to fruit and vegetables).

Sustainable Animal and Plant Production Systems

Innovations in this sphere range across scales from microbiome-related advances that entail interactions with plants and animals to genetic technologies applied to microbes, animals, and plants to agronomic and other systems-management innovations. Many of these innovations are most effective when combined, potentially leading to synergies enabling novel syndromes of production (Vandermeer 1997; Finckh 2008; Li et al. 2020a). As outlined above, innovations in genetics, breeding, and agronomy have contributed to huge improvements in productivity over recent decades, with a range of downsides that are increasingly recognized as unsustainable.

Crop innovations: The power of conventional breeding continues to benefit from myriad innovations that are collectively termed molecular breeding, which encompasses a range of technologies from identifying natural gene variants (alleles) of interest and selecting for them in breeding programs, to moving genes within or across species barriers through genetic engineering, as well as gene editing to alter alleles within a genome (Jaganathan et al. 2018). Crop improvement strategies with implications for food and nutrition include those that increase yields, those that stabilize yields and reduce losses, and those that change the nutrient content of the crops. Past yield increases have resulted from hybrid technologies, in which the superiority of the progeny of crosses between certain inbred lines has allowed for astonishing yield improvement over recent decades, most notably in maize (Reeves and Cassaday 2002). Breeding new crop varieties with high nutrient-use efficiency is an effective means to reduce fertilizer use without sacrificing crop yields (Shen, Li, et al. 2013; Jiao et al. 2016). Most often, this has enabled yield increases with stagnant fertilizer use patterns, as has been true for maize/corn in the US. The idea of improving yields through improved photosynthetic efficiency (e.g., C4 rice) is a long-shot bet in which substantial research resources are being invested (Ermakova et al. 2020). Another high-risk idea with potentially high returns is that of putting genes into cereals to enable the crops to fix nitrogen (Box 2).

For stabilization of yields, there are many natural alleles and transgenic strategies aimed at improving abiotic and biotic stress tolerance. Ensuring that plants and animals can withstand challenges from biological aggressors is an inherently dynamic challenge because weeds, insects, and pathogens all evolve to overcome the obstacles that they encounter. For example, crop germplasm (including the wild relatives of cultivated crops) often carries a wealth of resistance alleles that can protect crops from diseases and insect pests when the alleles are transferred to cultivated varieties. Unfortunately, genetic resistance often breaks down rapidly when pathogens and insects evolve to evade recognition or otherwise overcome defenses (Pilet-Nayel et al. 2017); such boom-and-bust cycles also occur with pesticides. Certain forms of resistance are harder to overcome than others, and some forms of resistance may come with tradeoffs related to yield or vulnerability to other biotic stresses. For example, breeding plants that resist mycotoxins can often lead to low-yielding varieties, and there is an urgent need to develop varieties that are resistant to toxins based on mechanisms that do not reduce yields. Elegant strategies have been devised for engineering resistance, either with gene transfer or editing, but the implementation of these strategies has generally been complicated by public concerns about—and resulting heavy regulation of—genetic engineering (see Box 2). While diverse pest management options abound, from breeding to biological control to landscape management, pesticide use remains a global and generally toxic default paradigm.

Similar innovations enable crops to more efficiently use nutrients like nitrogen and to cope with soil stresses such as water deficit, salts, and other abiotic challenges. Improving tolerance to transient flooding through the introduction of a gene sourced from a rice variety adapted to deep waters has been an impressive success story in rice (Bailey-Serres et al. 2010; Oladosu et al. 2020). While single genes with such strong effects on stress tolerance are relatively rare, most traits can be modified by conventional breeding strategies that change the allele frequencies of multiple genes with small effects on the trait. A diversity of approaches are being used by rice researchers worldwide to identify the genetic variation among domesticated rice species and their wild relatives that can be exploited to breed a new generation of "green super rice" varieties (Wing et al. 2018).

In addition to increasing and/or stabilizing food production, innovation in genetics and breeding has contributed to improving culinary and/or nutritional quality (or to reducing quality, when these aims are not considered). Biofortification aims to improve the nutritional quality of foods by improving plants' vitamin, mineral, and/or fatty acid profiles. This can be achieved based on genes that influence the levels of nutrients in food, such as increased levels of pro-vitamin A with transgenic golden rice or with conventionally bred orange-fleshed sweet potato. Improved nutrient content (or increased bioavailability and/or decreased anti-nutrient content) can also be achieved by selection for these traits in conventional screening and/or breeding programs.

Box 2: Transgenic and gene editing technologies

Following their commercial introduction in 1996, transgenic crops ("GMOs") are now grown on more than 190 million hectares (ISAAA 2019). The vast majority of transgenic plants currently grown contain only a few transgenes that contribute to pest management through herbicide tolerance and/or insect resistance genes. Plants expressing toxin genes from the bacterium *Bacillus thuringiensis* have been widely deployed, resulting in both crop-yield improvements and reductions in pesticide applications (Brookes and Barfoot 2018; Pixley et al. 2019). A variety of other strategies for engineered pest resistance have also been developed (NASEM 2016; Talakayala et al. 2020). A wide variety of technically effective transgenic methods exist for managing virus diseases, for example, some of which have attained some commercial success (Pixley et al. 2019). Papaya ringspot virus (PRSV) resistance was commercialized in Hawaii in 1998 (Gonsalves 1998). Transgenic papaya for PRSV resistance was approved for commercial cultivation in southern China in 2006 (Li et al. 2007) and has been planted there on a large scale. There are many other strategies for producing disease and insect resistance through gene transfer, which can be combined in transgene cassettes carrying multiple resistance genes (van Esse et al. 2020). For example, trials are being conducted in Uganda to assess potato lines carrying multiple resistance genes against late blight (Ghislain et al. 2019).

The traits in most widely cultivated transgenics target production-related priorities, mainly pest and weed management. Additional transgenic approaches have shown encouraging results for enhancing other production-related traits, such as drought tolerance (e.g., NASEM 2016; Gonzáles et al. 2020). Traits that more directly benefit consumers include those that are nutrition-related, such as vitamin, mineral, or fatty acid contents. The production in plants of omega-3 long-chain polyunsaturated fatty acids, normally sourced from fish oils, could reduce the pressure on oceans to supply this important nutrient that is often limited in diets. Products from the transgenic crops, carrying genes from marine microbes, can be consumed by livestock, fish, or humans. A number of other genetic innovations are currently in the pipeline with a focus on nutritional enhancement of crops and livestock (NASEM 2016; Napier and Sayanova 2020).

Extending the range of plants that can capture ("fix") atmospheric nitrogen (N) could benefit the environment by reducing the unsustainable production and use of synthetic N fertilizers (Charpentier and Oldroyd 2010; Galloway et al. 2013; Van Grinsven et al. 2013; Ladha et al. 2020). Natural substitutes, such as leguminous crops (beans, peas, and similar), can utilize N from the environment through symbiosis with root-associated bacteria that can fix N. Other types of plants, such as the major cereals, cannot form such productive relationships. Increased use of N-fixing crops would reduce energy and GHG emissions arising from fertilizer manufacturing. It could also reduce nutrient (especially N) losses into the air and water that contribute to both pollution and climate change.

Engineering crops, especially staple cereals, to fix N is a long-standing aim toward which plant breeders have made significant advances in recent years, although no new variety is anywhere near ready for widespread release. Several strategies are being undertaken to enable this, such as transferring the genes that control the development of root nodule symbiosis from legumes to cereals; creating nodule-independent N-fixing cereals promoting their association with endophytes that fix N; gene editing of associative N-fixing bacteria; and directly introducing nitrogenase into the plant (Mus et al. 2016; Vicente and Dean 2017; Rosenblueth et al. 2018; Van Deynze et al. 2018; Bloch et al. 2020). The tradeoff is that N fixation is metabolically expensive for legumes because they "feed" their symbionts carbon in return for the N fixed, so N-fixation would likely constrain yield potential in cereal crops. If the resulting yield reductions compel expansion of the agricultural frontier, resulting in the conversion of forest to croplands, the net environmental impact of N-fixing cereals could be adverse. It therefore remains to be seen whether, and when, cereal yields and associated environmental impacts could be enhanced by incorporating N-fixing capability in the absence of applied N.

Despite the commercial success of a few categories of transgenic plants, the approach remains controversial (Chvátalová 2019). As a consequence of this and the expense associated with clearing regulatory hurdles (US$7–35M out of a typical product development cost of US$136M; Phillips McDougall 2011), the transgenic crops in commercial cultivation use only a very small proportion of the genetic variation that could be accessed through this approach.

The more recent emergence of genome editing technologies (i.e., CRISPR/Cas), has made it possible to precisely alter gene sequences native to an organism. This is being widely applied to plant and animal species, as a powerful tool for genetics and breeding that may obviate some transgenic approaches (van Eck 2020; Mao et al. 2019). This technology can contribute to crop diversification by allowing rapid improvement of key agronomic traits in hitherto neglected crops, as recently shown by leveraging insights from tomatoes to improve plant architecture and fruit size in groundcherry (Lemmon et al. 2018). The regulatory environment for the utilization of this technology in agriculture—including the ethics of gene regulation—will largely determine the extent to which this technology contributes to crop diversification, protection, adaptation to climate-related stresses, and nutritional quality (Zaidi et al. 2019; Smyth 2020).

There seems no impending shortage of genetic engineering applications to effectively tackle disease resistance, abiotic stress tolerance, and desirable consumer attributes; the constraints to development, diffusion and equitable impacts largely stem from social and institutional forces (Pixley et al. 2019).

To date, the focus of genetics, breeding, and seed systems has been on the deployment of high-yielding starchy staples, with some shift of focus to more diverse foods in recent years. Even within the starchy staples, there has been an extreme emphasis on a few crops, which can make for vulnerability to climate events, pests, diseases, and other stressors. **Further investment in research beyond the major cereals could contribute to diversified cropping systems** that are better adapted to a range of environments (DeFries 2018; Mason-D'Croz et al. 2019). Focusing more research and innovation on a much larger range of plant and animal species could support the strategic diversification of food production and consumption, and help address the reduction in agrobiodiversity that has come with the focus on a narrow range of species. For example, more research on trees that produce fruits and nuts, as well as diverse vegetables and other more nutritious and sustainable food sources, could contribute to more resilient production systems and better diets.

Creating adapted and stress-tolerant germplasm is one set of challenges; ensuring that farmers have the germplasm they need is another. Seed value chains remain severly underdeveloped in many low-income countries (Ariga et al. 2019; Barriga and Fiala 2020). Facilitating the emergence of viable, reliable seed value chains is an essential first step in promoting adaptive genetic improvement research and farmer uptake of those improvements. Innovation in varietal evaluation and seed systems includes old and new strategies for working with large numbers of farmers to test varieties in diverse contexts (e.g., Bänziger and Cooper 2001; Van Etten et al. 2019). Plant breeding is, in any case, an important but relatively small component of the socio-technical strategies needed to build the climate resilience and sustainability of food systems. For farmers to implement more sustainable production practices, the innovations must be developed; farmers must be aware of them and have the knowledge, skills, and technologies needed to implement them; and producers must actually change their behavior. Experiences in the commercial, public health, and agriculture sectors illustrate that interpersonal contact can be essential in driving large-scale behavior change (Gawande 2013). Large-scale agronomic studies are being conducted in

China based on the "Science and Technology Backyard" (STB) system that links smallholder farmers with extension and research through a village-level innovation platform (Box 3), and elsewhere using farmer research networks and related approaches (Nelson et al. 2019; Van Etten et al. 2019). These methods show tremendous promise for drawing together the wisdom of (small farmer) crowds with the knowledge of cutting-edge scientific researchers to accelerate discovery, adaptation, and diffusion.

Box 3: Science and technology backyards—linking farmers, extension, agribusiness, and science at scale[8]

In China, tens of millions of small-scale farmers have implemented resource-conserving and yield-enhancing farming techniques through the STB initiative. The STB approach also gives researchers large datasets in near-real time to establish what works for whom through the participatory research and extension built into the approach. STB began with the observation that established training methods were not leading to substantial smallholder adoption of innovative cultivation methods; few farmers changed their practices even if they knew of the technologies. This recognition inspired China Agricultural University (CAU) researchers to strengthen their engagement with farmers. Recognizing the key role of trust, and understanding the importance of two-way information flow to support agroecological intensification, CAU scientists began a participatory research and training effort in Quzhou in 2009.

The researchers moved their research programs from the experimental station to the village so they could work and communicate directly with farmers, to share in their successes and failures. They rented a backyard in the village, and lived, worked, and studied in the yard. Professors and postgraduate students conducted intensive farmer participatory trainings. Gradually, farmers were attracted to the backyards, which became science and technology dissemination focal points in local communities. Trained farmers adopted high-yield and high-efficiency technologies (e.g., formulated fertilizer, sowing technology, and efficient water and fertilizer use techniques) at much higher rates than did untrained farmers (Shen, Cui, et al. 2013; Jiao et al. 2019). The effort then scaled up dramatically.

[8] We thank Xiaoqiang Jiao and Fusuo Zhang for contributing to the content of this box.

STB is now a multi-actor innovation platform located in rural areas that links the scientific community with smallholders, local government, and private enterprises to facilitate information exchange and technological innovation for achieving sustainable intensification of agriculture. The platform consists of farmer field schools, participatory on-farm research, new technology demonstrations, and farmer interest groups or clubs. Farmers get rapid and context-relevant responses to their challenges. Companies contribute their technologies and funding, quickly learning what works and what doesn't. Local governments provide supportive policies and extension services, earning constituent support.

In 2020, 127 STBs operate in 23 provinces and regions with the participation of 29 scientific research institutes and over 100 agricultural extension stations in China. The STB system covers 45 major crops and has allowed significant scientific insights to be made, while facilitating transformative change that both improves yield and decreases the environmental footprint of agriculture (W.F. Zhang et al. 2016; Jiao et al. 2019). In 2019, FAO partnered with CAU and African countries to promote STB for enhancing transformation of African agriculture, starting with 34 students from eight African countries training at CAU before returning to their home countries to implement STBs (Jiao et al. 2020).

Livestock innovations: The livestock sector is often blamed for contributions to communicable and non-communicable disease burdens and to greenhouse gas production. But while reduced meat consumption is recommended in industrialized food systems, greater meat consumption would be beneficial to health outcomes in many low- and lower-middle income countries (FAO 2020). Tens of millions of resource-limited households derive their livelihoods from livestock and improving productivity in the sector can contribute to improving nutrition and pro-poor development in general (ILRI, 2019). Many actions can boost productivity including improved grazing, better disease management, and closer integration with other on-farm enterprises such as crop production. Two areas of innovation are highlighted below: improved livestock breeding and feeds.

Sophisticated livestock breeding methods have been applied to improve livestock productivity. Advanced genetic and genomic selection methods have the potential to contribute to heat tolerance and to methane mitigation (Pryce and Haile-Mariam 2020; more on the latter issue below). Livestock breeding efforts that focus on other production traits tend to reduce heat tolerance, which is problematic as temperatures rise with climate change. This trend requires attention to breeding for heat tolerance. An example is the "slick hair" trait, which increases thermotolerance and productivity in Holstein cows (Ortiz-Colón et al. 2018). While prospects exist for accelerating traditional breeding processes for desired animal traits (Strandén et al. 2019; Barbato et al. 2020), an integrated approach will require both technical and social adaptations (Menchaca et al. 2020). Many indigenous livestock breeds and populations remain uncharacterized, particularly in Africa, and much is unknown about their cross-breeding potential. Increasing the attention focused on a wider diversity of locally adapted species, including small stock such as guinea pigs, sheep and goats, may increase production in niches important to the food security of vulnerable populations.

Innovations in feed value chains can address a range of AFS dysfunctions. Examples include feed-based strategies for reducing methanogenesis in ruminant digestive systems to reduce greenhouse gas production in the livestock sector; reducing the depletion of fisheries stemming from the use of fish-based fish food; and improving the levels of omega-3 in animal and human diets. Algal-derived feed supplements can be used to substantially reduce enteric methanogenesis in ruminants (McCauley et al. 2020). Furthermore, synergies have been observed between the effects of algal biomass on methane production and livestock productivity.

Another innovation is the use of insects as feed. Insects are often rich in protein and some vitamins and minerals. In the EU, black soldier fly (BSF), yellow mealworm and the common housefly have already been identified for potential use in feed products (Henchion et al. 2017). Use of some insect-derived protein may reduce GHG emissions, though strong evidence on this impact remains scant (Parodi et al. 2018). Insect-based feeds are currently advanced mainly for their nutritional, environmental, technological and socio-economic impacts.

Consumption of fish and shellfish is recommended for personal and planetary health (Willet et al. 2019). A variety of innovations are improving the prospects for sustainable production of these foods. As world fisheries decline with increased anthropogenic and climate stress on the world's oceans, aquaculture has become an increasingly important source of fish and shellfish, especially in the Global South. Production from low- and middle-income countries in South Asia, Southeast Asia, and Latin America is increasingly responsible for the growth of global aquaculture and shows considerable future promise (De Silva 2012; Gentry et al. 2017). Well-designed aquaculture systems can deliver nutrient-rich foods with low environmental impact (Shepon et al. 2020).

Much of the ocean's fish catch is used to feed farmed salmonids (salmon and trout) and shrimp. Shifting away from the inclusion of fish meal in aquafeed could enable aquaculture farms to produce high-value products like salmon and shrimp without depleting the ocean's fisheries or expanding current, less sustainable feed-cropping systems such as soy and canola (Fry et al. 2016). Options to reduce the environmental footprint of fish feed include insects, such as BSF and algae, both of which can be grown using side products (i.e., potential wastes; see Box 4). Likewise, single cell proteins (SCPs) produced via fermentation are also ideal fish meal substitutes, and some use methane as feedstock, making them even more sustainable. Another option is camelina, an oilseed crop that can be used as an animal feed to enhance omega-3 levels (Berti et al. 2016). In addition, it is well adapted to genetic manipulation and so can also be used to produce very high-value lipids (Yuan and Li 2020).

The genetic diversity of farmed fish is currently low, and pests and diseases may be poorly controlled in ways that are harmful to the environment and human health (e.g., Cabello et al. 2013). The diversification of aquatic species used in aquaculture could reduce pest and disease pressure and provide a wider range of options for cultivation in different environments. New aquaculture production models are emerging to tackle environmental issues such as eutrophication and mangrove loss, including land-based recirculating aquaculture systems (RAS), inland coastal flow-through systems for salmon and indoor farms for shrimp, and ocean-based closed containment systems. RAS is an especially promising technology, offering the potential to grow seafood entirely indoors with minimal environmental impacts. In these systems water is continuously reused, and fish waste, uneaten feed, nitrates, and microorganisms are filtered out. Current species approaching commercialization potential include salmon, trout, tilapia, kingfish, barramundi, and shrimp.

Agroecological innovations: The varied challenges created by modern agriculture can be addressed, at least to some extent, by a shift from reliance on hydrocarbons-based inputs to the application of approaches that are based on agroecological principles such as efficiency, synergy, and circular economy (Barrios et al. 2020). Similar concerns and approaches are described in literatures associated with the terms "regenerative agriculture" and "agroecology." The field of agroecology (AE) entails "the study of the interactions between plants, animals, humans and the environment within agricultural systems" (Dalgaard et al. 2003). The term AE is also used to refer to the science, practice and movement related to the ecological and social processes that underlie and influence farming and AFSs (Wezel and Soldat 2009). Holistic approaches to AE consider both technical and social levels through interconnected innovations that can work together to transform food systems towards greater sustainability (HLPE 2019). The concept of agroecological transition has been highlighted in a number of recent reports and case studies (IPES-Food 2018; NatureScot 2020).

Gliessman (2016) outlined a series of stages that can support a transition to ecologically based agriculture. The first stage is raising efficiency. Increasing input use efficiency is a major focus of "sustainable intensification" (e.g., Godfray et al. 2015). Important improvements in nutrient-use efficiency are being achieved by precise placement of designed nutrients in the root zone, with the quantities, composition, and timing of application guided by models (Shen, Li, et al. 2013; Wang and Shen 2019). This approach can support increased yields via root-soil-microbial interactions (Wang and Shen 2019; Wang et al. 2020). Strategic nutrient application has also been coupled with intercropping to improve yields and nutrient use efficiency (Li et al. 2007). A range of integrated soil fertility management (ISFM) practices similarly couple use of external inputs as essential complements to more effective use of organic materials from within the system (Place et al. 2003; Vanlauwe et al. 2010, 2015).

The second level of agroecological transition involves substituting natural processes for excessive use of chemical inputs. This includes the integration of legumes into cereal-based systems to bring in nitrogen, or crop-livestock integration as another alternative source of crop nutrients. While modern agriculture has relied on toxic chemicals to manage pests (i.e., insects, weeds, and pathogens), ecologically friendly management options have been, and are being, devised especially to combat emergent pesticide resistance as insects and pathogens evolve in response to chemical controls. "Biological control" can involve the use of native natural enemies, encouraged through landscape management, as well as introduced predators of pest species and microbial antagonists of pests. Spectacular outcomes have been achieved towards managing the cassava mealy bug (Herren and Neuenschwander 1991) and the pearl millet head miner (Ba et al. 2014), for example, through the introduction of parasitoid insects that prey on the pests, and there are many new possibilities for biological control (van Lenteren et al. 2018). Box 4 focuses on regulatory approaches that could break the current pesticides lock-in.

The third level of agroecological transition entails redesigning production systems to avoid problems and drawing upon new agroecological principles and processes (Krebs and Bach 2018; Pretty et al. 2018; Barrios et al. 2020; Wezel

INCREASING DIVERSITY CAN PROVIDE A RANGE OF BENEFITS THAT COLLECTIVELY IMPROVE SYSTEM RESILIENCE.

et al. 2020). This may entail new crops, as well as the integration of crops, trees, and livestock, and nutrient flows between rural and urban areas. **Increasing diversity can provide a range of benefits that collectively improve system resilience**. For example, a long-term study of diversification via crop rotation showed that maize yields were higher with more diverse rotations, even under drought conditions (Bowles et al. 2020). Although crop diversification is hardly a novel idea, shifting from monocultures and other low-diversity systems towards greater agrobiodiversity may involve innovation in breeding, agronomy (potentially including engineering), and markets (IPES-Food 2016). In a variety of contexts, redesign of integrated crop-livestock systems can offer environmental and economic benefits. For example, Bonaudo et al. (2014) cite examples of successful application of agroecological principles towards improving system performance through crop-livestock integration in Brazil (reducing deforestation in the Amazon) and in France.

System redesign will entail diversifying production systems in time and space, considering the integration of crops, livestock, and trees—as well as external inputs—on farms and across landscapes. Diversity at these scales has implications for nutrient cycling, natural pest regulation, risk management, and, in some contexts, the diversity of consumption. Modern agriculture has too often reduced diversity; reversing this trend will require new approaches to landscape management, taking into account the interests of multiple stakeholders and the ecosystems services they require (Moraine et al. 2014; Martin et al. 2016). At the same time, we must guard against overcelebration of diversity as an end unto itself lest we risk locking in a low productivity status quo among smallholder producers who need external inputs, and perhaps greater partial specialization in order to escape poverty. The point is the need to tap the best insights of both the AE and sustainable intensification approaches and to customize solutions to specific contexts rather than paint with too broad a brush.

Plant and animal breeding can be regarded as combinatorial genetics; breeders use recombination and selection to put together not only the best alleles but also the sets of alleles that harmonize best with each other. Similarly, combinatorial agronomy has the potential to more fully exploit the interactions of genotypes with environments, as well as the interactions of multiple crop varieties and species in diversified systems. Plant varieties and species can synergize based on complementarity of resource use, as well as less obvious biochemical interactions (D.S. Zhang et al. 2016; Wen et al. 2019; Zhang et al. 2020). In addition, the performance of plants and animals can be influenced by the microbes associated with them. For example, certain root-associated microbes can enhance nitrogen fixation in legumes, and others can benefit wider ranges of plant taxa.

Growth-promoting Rhizobacteria, for example, can greatly enhance the performance of potatoes grown under biotic and abiotic stresses (Grossi et al. 2020). The effective design and implementation of biodiverse landscapes is a combinatorial challenge that, unlike plant breeding, cannot easily be conducted by the private sector alone. Large-scale public engagement in innovative-farming system design can be facilitated by digital technologies and collaborations such as the Science and Technology Backyard (W.F. Zhang et al. 2016; Box 3) and the farmer research network approach (Nelson et al. 2019).

Diversified crops and systems, together with markets that support people's access to diverse foods, provide a wide range of options for improving dietary nutrient intake. There is a complex relationship between the diversity of production and the diversity of diets, but there seems to be a strong positive relationship between agricultural biodiversity and dietary diversity in smallholder systems (Sibhatu et al. 2015; Jones 2017a, b; Sibhatu and Qaim 2018; Tobin et al. 2019). Diversity can offer a variety of important ecosystem services, from reducing epidemic potential (King and Lively 2012) to enabling different species to tap soil, water, and light resources in complementary ways that improve yields (Li et al. 2020b; IPBES 2019). Plants can also be biofortified based on improving fertilizer use, either in the field or in controlled-environmental contexts; this does not require genetic modification (Pannico et al. 2019). Levels 4 and 5 of Gliessman's framework for agroecological transitions entails reestablishing connections among those who produce and consume food, and building a new global food system based on greater equity and justice (Gliessman 2016). Much of this report focuses on the mechanisms that could deliver on the HERS objectives that are shared by those in the agroecology movement and by others who may have different foci and couch their arguments in different language.

Box 4: Regulatory nudges towards integrated pest management

A substantial proportion of crops are lost to pests, which are broadly defined as including the weeds, microbes, and insects that reduce yields (Oerke 2006). Despite many well-known downsides and alternatives (Sánchez-Bayo and Wyckhuys 2019), pesticides remain the global standard approach to managing pests. The effectiveness of the pesticide solution is showing signs of wear. Over the past several decades there has been rapid increase in the evolution of biological resistance to crop protection compounds (Gould et al. 2018), and concern is growing over the environmental and health impacts of pesticides. There are a wide variety of integrated pest management (IPM) alternatives, though some IPM methods may be more complex to operationalize than spraying pesticides. Regulatory pressure is needed to enable a general shift from synthetic pesticides to agroecologically-based IPM approaches.

Regulatory frameworks for the crop protection industry currently vary greatly, with the strongest regulation in Europe and the weakest in many LMICs. Most current regulations in the US focus only on the active ingredient, while a growing body of research has shown that other components of product formulation can be as toxic as active ingredients (Benachour and Séralini 2009). Because agricultural intensification in LMICs has the potential to increase the use of pesticides, regulatory environments need to be strengthened in these areas to ensure the safety of workers, consumers, and the environment. Farmers in Africa are increasingly dependent on pesticide use, with associated human health costs (e.g., Sheahan et al. 2017).

Regulations should require that products be able to be used safely. In low-resource contexts, farmers may lack access to personal protective equipment (PPE) necessary to manage chemicals safely, or existing PPE may be inappropriate for use in local environments—such as heat-trapping slickers used in hot, tropical environments where temperature increases are known to have physiological effects on workers (Masuda et al. 2020). Also, many potential users may not be literate in the languages in which safety guidance is provided. Some crop protection companies have committed to the improvement of training for farmers, but requirements should be introduced such that registration of a product in a market segment is not allowed unless it has been clearly demonstrated that most farmers can use it safely.

Many agroecological principles and practices can be used to manage pests without the use of synthetic pesticides or in a manner that can at least sharply reduce pesticide use. The use of host plant resistance is already widespread, though seed companies that benefit from pesticide sales tend to focus on improving yield potential rather than resistance in their breeding programs. The use of biodiversity (greater diversity of crop species and varieties, strategically deployed in time and space) can reduce pest pressure and epidemic potential (McDonald 2014), while potentially contributing to system resilience and dietary diversity. Botanical pesticides (e.g., chemicals derived from plants—often local weedy species) have proven to be useful in pest management even in very low-resource environments, often reducing pest populations without harming the pests' natural enemies (Stevenson et al. 2020; Sola et al. 2014). Biological control agents, including microbial pesticides, can be very specific and effective (van Lenteren et al. 2018; Lednev et al. 2020).

The crop protection industry's current profit model is based on the volume of product sold. A shift in the business model to provide a service—pest management—rather than a product could push the industry to develop new mechanisms for monitoring and managing pests. In such a model, chemical inputs would be a cost to the service, rather than the primary source of revenue. Promising IPM approaches would likely be amplified because of their potential lower cost per acre. There would also be incentives to target that limited chemical use to specific locations in a field and at specific times to minimize the development of resistance. The industry could license digital tools that identify, track, and provide targeted recommendations for sub-field pest management approaches.

Soil health innovations: Soil health poses a fundamental challenge to agriculture in all AFSs. The application of mineral fertilizers can temporarily obviate productivity constraints posed by specific nutrient deficiencies (especially N) and can, but does not always, support the maintenance of soil organic matter (SOM), which is fundamental to soil health. The organic component of soil is especially critical to its structure, ability to cycle nutrients, resistance to erosion, regulation of hydrological processes, facilitating recharge, and water holding capacity. A rule of thumb holds that for every 1 percent organic matter in soil per hectare, 100,000 liters of water can be held by the soil. SOM depletion is an especially severe threat to much of Africa and parts of South America, where soils are ancient and weathered and SOM has been depleted to the point that it cannot support crop growth. Strategies to boost SOM must be adapted to local soil conditions and management options, sometimes requiring increased external inputs of inorganic nutrient amendments and in other cases reduced application rates (Amelung et al. 2020).

Challenges related to soil, water, and climate are interrelated, so their solutions need to be considered and approached in an integrated way. SOM is one of the earth's main carbon pools. It can either sequester or release carbon, and thus has a key role in the global dynamics of GHGs. The French government has announced the aspirational "4p1000" initiative, on the premise that climate change could be halted if carbon were returned to soils at an annual rate of 0.4 percent. Climate change is working against us. The increasing temperatures associated with global warming make organic matter less stable, and violent rain events contribute to soil erosion and loss of organic matter. Land management approaches that build and maintain soil carbon can both reduce GHG emissions and sustainably improve food and feed production. These approaches include landscape management to reduce erosion, including agroforestry; and the use of cover crops, especially leguminous species that fix nitrogen and access poorly soluble forms of phosphorus by carboxylate exudation from roots (Lyu et al. 2016; Griscom et al. 2017; Wen et al. 2019). A challenge, however, is that more marginal lands and soils—where a disproportionate share of the rural poor reside—cannot sequester much carbon per unit area. Investments to build soil carbon can thereby inadvertently exacerbate economic inequality without companion interventions to help those in marginal areas.

An especially promising option is increased use of carbon and other nutrients recovered from organic waste, including food waste, industrial waste (e.g., coffee cherry, sugarcane bagasse, sawdust, animal bones), as well as human and animal waste (urine and feces). The volumes involved, and the negative health and societal effects of these waste streams, are enormous, as are the potential benefits of recycling and reuse (Berendes et al. 2018; Mihelcic et al. 2011). Many sources of organic matter currently lead to GHG emissions and air and water pollution (e.g., nutrient loading of aquatic environments causes toxic algal blooms). Human, animal, and other organic wastes have historically been used as fertilizers, but these practices have eroded for a variety of good reasons for which there are now technical solutions.

The recovery of nutrients and organic matter from waste streams into agriculture could provide a wide array of benefits—including improved sanitation, reduced pollution, reduced GHG burden from agriculture, improved climate resiliency, improved crop production, and improved health of soils and people—contributing to achievement of most SDGs (Orner and Mihelcic 2018). Sewage sludge has fertilizer value but also the potential to contaminate soils and foods because of industrial wastes that can enter sewage systems. A large fraction of humanity is not served by sewers in any case; 2.3 billion people lack even basic sanitation, and the excreta of 4.5 billion goes into the environment untreated (WHO and UNICEF 2017). Container-based sanitation can circumvent these problems (Russel et al. 2019). Technical developments can facilitate resource recovery into agriculture, with a diversity of options that can be adapted to different contexts (Harder et al. 2019). No single step in waste-to-value chains is prohibitively challenging, but large-scale implementation would require considerable political will and social adjustment to overcome a range of barriers to implementation.

A key barrier is the distance between the urban locations where most waste originates and the peri-urban and rural loci of most agricultural production, which often makes transport of low value-to-weight waste products prohibitively expensive. This will often require low-cost processing to increase the value density of recovered waste by products. Such processing techniques are themselves important areas in need of innovation.

A key challenge associated is that improving soil health is a slow-moving process, with many soil features being non-obvious and longer-term. Innovations in soil health include the development of toolkits that enable people (farmers, ranchers, and other land managers) to discern what is happening to soils more quickly, cheaply, and reliably. Conventional soil testing is done in laboratories, using methods that require considerable time, expense, and expertise. New methods allow more farmer-friendly assessments, as well as remote sensing of soil features (Magonziwa et al. 2020). Several teams are developing lower cost, higher spatial resolution methods to assess soil chemistry (organic constituents, inorganic macro- and micronutrients, pH, etc.), biology (microbes and macrofauna) and physics (structure, including aspects that influence water infiltration and absorption). The use of spectral methods, including those that utilize low-cost, hand-held spectrometers, as well drone-based and satellite-based ones, is rapidly bringing down the cost and speed of access to soil-related data (Angelopoulou et al. 2020). Spectral methods must be complemented by digital soil mapping that leverages site-based measures, satellite-based covariates, and artificial intelligence methods to predict at scale soil properties (e.g., micronutrient availability) that are not especially amenable to detection by spectral methods.

The capacity to generate reliable, affordable, farm- or field-specific soil indicators and fertilizer recommendations remains limited, however. Errors inevitably arise in soil sampling and chemical analysis procedures within and among laboratories, and in algorithms predict soil conditions based on a few imperfectly observable indicators. The marketing of technology-based advances in soil information services currently overreaches their capacity to deliver (Schut and Giller 2020), much as has been

DIVERSIFICATION OF PRODUCTION CAN CONTRIBUTE TO HEALTHY DIETS BY PROMOTING DIETARY DIVERSITY, ESPECIALLY AMONG SEMI-SUBSISTENCE SMALLHOLDER FARMERS.

broadly the case for index insurance products intended to provide farmers with low-cost, context-specific risk management products (Jensen and Barrett 2016).

Sustainable production-system innovations connect to several of the food-system design objectives outlined above. Perhaps agroecological intensification's chief benefits relate to environmental sustainability: curbing the expansion of farmed land at the expense of nature, as well as reducing pollution associated with the indiscriminate application of fertilizers and pesticides. **Diversification of production can contribute to healthy diets by promoting dietary diversity**, especially among semi-subsistence smallholder farmers (Sibhatu et al. 2015; Sibhatu and Qaim 2018). Improving soil health can improve resiliency to drought spells, thereby improving the productivity on marginal (and other) lands (Lal 2016).

By reducing plant stress, healthy soils can also reduce a widespread food safety issue: the problem of mycotoxin contamination. Mycotoxins are toxic metabolites produced by a range of micro-fungi that colonize foodstuffs (most notably, maize, groundnuts, tree nuts, and spices) before and after harvest. The best known are aflatoxin and fumonisin, but hundreds of other mycotoxins contaminate the world's food system. Aflatoxin, the most potent naturally occurring compound known, causes liver cancer, growth stunting, and immunosuppression (Routledge et al. 2016); it contaminates a quarter of the world's foodstuffs at levels above regulatory limits, and up to 80 percent at detectable levels (Eskola et al. 2020). There are many interventions that can be used to minimize or manage mycotoxins along food value chains, but ensuring soil health is fundamental, as stressed plants are most vulnerable to fungal colonization. Crop genotype, as well as harvest and post-harvest conditions and processes, also influence mycotoxin accumulation and exposure. Boosting food safety commonly requires multiple complementary interventions.

Alternative, Land-Saving Nutrient Production Systems

At least four distinct, rapidly-advancing classes of innovation are already beginning to facilitate de-agrarianization. The costs of production in this space are dropping quickly as private investment pours into novel technologies that promise to reduce the land and ocean footprint of food production.

The first involves the emergence of nutrient-dense food and livestock feeds based on microalgae, insects (e.g., BSF larvae), etc., as substitutes for land-intensive cereals and oilseeds-based proteins and fish meal. The livestock sector accounts for 40 percent of the world's agricultural GDP and contributes to the livelihoods of 1.3 billion people (Herrero et al. 2013). Feeding animals also accounts for a large share of agriculture's environmental footprint. Assuming continued or growing demand for protein concentrate for livestock feed to meet rising demand for animal-source foods, alternative livestock feeds that utilize currently neglected resources could reduce the environmental footprint of meat and aquaculture production, while also reducing pollution from other sources and ensuring affordable and equitable access to these nutrient-rich foods.

Several multinationals have made strategic investments (often through collaborative ventures) in this field, with prominent examples such as Nestlé and Corbion,[9] as well as Unilever and Algenuity,[10] for microalgae food innovations; or Buhler and Protix[11] for insect-based food and feed. The unit-production costs of these novel alternatives are falling fast, and they should be able to compete commercially this decade with soymeal, maize, hay, fish meal, and other conventional feeds. Research shows that these feeds are scalable, yield animal-sourced foods of similar quality and safety as those based on conventional feeds, and potentially offer added health benefits (Caporgno and Mathys 2018; Smetana et al. 2019; Altmann et al. 2020; Cottrell et al. 2020).

Box 5: Microbial, insect, and algal biomass as circular feeds

Insects, themselves a miniature form of livestock (Barroso et al. 2017), have many advantages in feed value chains (van Huis 2013) for the rearing and maintenance of fish and shellfish, chickens, pigs, and pets. For example, black solider fly larvae (BSFs) can be fed organic wastes from industrial or

[9] See press releases at https://www.corbion.com/about-corbion/press-releases?newsId=2199459 and https://www.nestle.com/randd/news/allnews/partnership-corbion-microalgae-plant-based-products, or press coverage at https://www.foodnavigator.com/Article/2019/11/07/Nestle-and-Corbion-eye-microalgae-for-next-generation-plant-proteins#.

[10] See press coverage at https://www.foodnavigator.com/Article/2020/07/30/Unilever-and-Algenuity-discuss-the-potential-of-microalgae-Algenuity-s-technology-unlocks-a-wealth-of-food-applications#.

[11] See press coverage at https://www.feednavigator.com/Article/2017/06/27/A-new-Dutch-plant-will-be-the-first-in-Protix-and-Buhler-insect-tie-up.

municipal sources, such as food scraps and excreta from humans and animals (Gold et al. 2018), and used to produce the high-quality protein, fats, and other nutrients that are needed for livestock and humans (Patel 2019; Smetana et al. 2019). BSFs are tolerant of certain toxins, such as pesticides and mycotoxins, providing a disposal alternative for contaminated foodstuffs. Among other animal protein sources, BSF (either as a puree or meal) has a low carbon footprint and low potential for ozone depletion, acidification, and eutrophication impact (Smetana et al. 2019). The BSF market is projected to grow to more than US$2.57 billion by 2030 (Byrne 2020) and has already entered middle-income country markets such as Indonesia.[12]

BSF cultivation also has the potential to contribute to human waste management, thus providing an avenue towards achieving SDG 6, which concerns ensuring access to water and sanitation. Most human excreta and other organic wastes currently go untreated into waterways, with 92 percent of wastes being untreated in low-income countries and 80 percent untreated at a global level (Sato et al. 2013). The use of organic wastes for BSF production could improve water quality and safety while producing high-quality feed. A concern about BSF-based waste utilization relates to chemical and microbial safety. For example, the possibility of heavy metal contamination was demonstrated, as BSFs bioaccumulate heavy metals present in their diets. (BSFs have, thus, been considered for bioremediation [Bulak et al. 2018].)

Single cell proteins (SCPs) offer another high-potential source of nutrition for inclusion in feed for aquaculture and livestock. SCPs are protein meals based on microbial or algal biomass, and can be produced by yeast, bacteria, microalgae, and protists. These microorganisms generate proteins after consuming sustainable feedstocks including methane, wastewater, industrial and agricultural residues, methanol, syngas, and second-generation sugars. SCP manufacturers are scaling up operations globally, including commercial-scale plants in the developing world (Jones et al. 2020).[13]

[12] A BSF demonstration facility in Indonesia has completed final evaluation. See press coverage at https://www.eawag.ch/en/department/sandec/projects/mswm/forward-from-organic-waste-to-recycling-for-development/.

[13] See, for example, Calysta's entry into China https://www.undercurrentnews.com/2020/06/30/calysta-adisseo-aquafeed-joint-venture-to-build-first-plant-in-china/.

Microalgae are another valuable, well-rounded source of biomass, protein, oils, and minerals for aquaculture, livestock, and human consumption. Fish and fish oils are valued in human diets for their high omega-3 fatty acid contents, which are derived from the microalgae on which they feed. Sourcing these high-value oils directly from microalgae could reduce offtake pressure on marine fisheries, which are the main current source of fish meal and fish oil feeds.[14]

Lutein, a widely used carotenoid for food coloring as well as a dietary supplement, is sourced from microalgae. Lutein-rich spirulina microalgae (cyanobacteria *Arthrospira*) are used as a supplement for fish and human nutrition (Shah et al. 2018). Microalgae can be farmed in marine or closed-loop production systems to produce food and feed, while capturing nutrients that can otherwise damage aquatic resources. Contained production systems can be designed at varying scales, either with controlled lighting or in the dark with controlled carbohydrate inputs. However, due to limited technology readiness levels and economies of scale, both types of production systems are energy intensive and require substantial capital investment in many regions (Smetana et al. 2017).

The second class of innovations rely on tissue engineering methods that culture cells to grow animal tissue outside the body, without the environmental, animal welfare, or financial costs of raising and slaughtering live animals. These "clean" or "cellular" meats have attracted considerable private investment and media attention. The commercial threat these products pose to conventional livestock producers has already prompted legislative and regulatory battles in some OECD economies over product labeling (i.e., what constitutes "meat"). Although these products remain expensive, unit costs are dropping fast and are predicted to fall to the level of conventional ground beef by 2026 (Tubb and Seba 2019).

[14] In 2017, a joint venture between DSM Nutritional Products and Evonik Nutrition & Care was announced to invest around US$200 million in a new facility, delivering omega-3 fatty acid products for the fast-growing animal nutrition and aquaculture markets. See press coverage at https://www.nutritioninsight.com/news/DSM-Evonik-Collaborate-on-Marine-Algae-for-Animal-Nutrition-Aquaculture.html.

The third group of land-saving food innovations relies on controlled environment agriculture (CEA)—so-called "indoor" or "vertical" farming—much of it based on aero-, aqua-, or hydro-ponic methods. CEA is growing quickly to serve urban middle- and upper-class consumers in OECD and Asian countries. Its comparative advantage lies in year-round localized supply chains delivering consistent-quality, high-value, short-cycle horticultural products (Pinstrup-Andersen 2018; WWF 2020). Falling electricity costs and more reliable and affordable small-scale (e.g., rooftop) renewable energy generation increasingly obviates CEA's loss of free sunshine to stimulate plant photosynthesis. But especially in an environment of low borrowing costs to enable firms to invest in capital-intensive CEA methods, and in the face of increasing water scarcity that is more easily managed in compact spaces than in large, open fields, CEA is becoming increasingly viable as a means of expanding the supply of leafy greens and fast-growing (i.e., not tree-based) fruits.

The fourth group of innovations uses microbes and fungi to produce novel foods through a process broadly known as "precision fermentation." Fermentation is a centuries-old process used to make beer, cheese, etc., in virtually every culture globally. Recent advances in synthetic biology now enable labs to design micro-organisms (e.g., bacteria, microalgae, or yeasts) that produce more complex proteins from inexpensive feedstocks. This is the technology behind rapidly growing commercial enterprises such as Beyond Meat, Impossible Foods, and OmniFoods. This technology is not new; Quorn has employed the versatile mycoprotein since 1985 to make meat analogues. But precision fermentation has been taking off in the past few years as advances in (especially synthetic) biology have enabled cost reductions and improved customization of target proteins. In the first seven months of 2020 alone, these technologies attracted at least US$435 million in new investment, more than 3.5 times the capital raise by cultured/cellular meat companies globally (Shieber 2020). Precision fermentation methods can likely scale at costs below those of conventional systems for producing animal-source foods, generating a promising alternative to meet rapidly growing demand for more complex proteins without needing intermediation by livestock (Buckler and Rooney 2019; Tubb and Seba 2019).

As incomes increase, rapidly growing demand will inevitably deepen further for each of these de-agrarianized methods. Rising income, urbanization, and increased demand for shorter supply chains, and growing consumer concerns about nutrition, food safety, animal welfare, and the environmental impacts of conventional farm production methods will reinforce the momentum behind novel, land-saving food production methods, especially as companies and policymakers work to overcome consumers' natural skepticism about novel products

(Siegrist and Hartmann 2020). **The opportunity arises for technological leapfrogging in Africa and Asia**, in particular, as promising technologies that were previously unaffordable (e.g. CEA, precision fermentation) are becoming commercially viable at scale any place with reliable energy, adequate urban market size, and a literate workforce with sufficient basic scientific training. LMICs can use rural lands to farm carbon, solar, wind, and geothermal heat, not just crops and livestock, while simultaneously deploying novel technologies to design and deliver healthier foods—and remunerative urban and peri-urban jobs—based on shorter supply chains to meet growing urban food demand. In so doing, we can convert agri-food sectors from a GHG source to a sink, shift nutritional transitions in a healthier direction, and facilitate a structural transformation that harnesses looming demographic changes to simultaneously boost sustainability, resilience, inclusion, and healthy diets.

As promising as these land-saving methods are as a means to address sustainability, healthy diets, and resilience objectives simultaneously, they risk major social disruption, especially in rural areas that heavily depend on conventional farming. Major technological change inevitably unleashes what Joseph Schumpeter (1942) famously termed "creative destruction." **Without a concerted effort to transition rural economies, as lower costs of de-agrarianized food production increasingly undercut the profitability of conventional livestock and feed crop production, we run a real risk of a cascading calamity of farm bankruptcies, farmer suicides, and rural unrest**.

So what alternative sources of income exist for agricultural landowners and workers? We see at least three options. The first is renewable energy production, demand for which is growing rapidly around the world, especially as technological advances continue to drive down the costs of generating electricity from geothermal, solar, and wind sources and as off-grid alternatives have become increasingly viable. Lease royalties from energy companies and power utilities, and the non-farm value addition made feasible by reliable local power generation open up new livelihood options for agricultural communities. Indeed, there is reinforcing feedback between renewable energy production and novel, non-farm food production methods because cost-reducing technological change in one sector helps lower costs in the other. Relying just on unregulated energy markets and AVCs, therefore, seems a high-risk strategy for rural communities.

A second option is for governments to implement carbon taxes and invest more in establishing viable emissions trading systems (i.e., carbon markets) and the digital technologies necessary for low-cost, reliable verification of GHG fluxes to support monetizing sequestration activities. The current global average carbon price across both regulated and voluntary markets is only US$2/tCO2, far below the US$40–80/tCO2 range necessary to cost-effectively reduce emissions in line with the Paris Agreement (HLCCP 2017; World Bank 2020). GHG sequestration is feasible in regenerative agriculture using sustainable farming practices, although concerns remain (Schlesinger and Amundson 2019). These environmental services can generate mitigation benefits to supplement agricultural earnings as farms diversify into harvesting GHG, solar, and wind, as well as commodities.

The third option is payments for ecosystem services (PES), which have grown popular worldwide, with an estimated US$40 billion or so in annual transactions (Salzman et al. 2018), with estimates for the potential revenues to the US' agriculture sector alone ranging as high as US$14 billion (Informa and IHS Markit 2018). PES have clearly demonstrated favorable impacts when well designed, although a range of design flaws continue to impede broad use and may limit sustainability gains (Jayachandran et al. 2017; Jack and Jayachandran 2019). Thus, PES are useful instruments, but no panacea. They appear to work most effectively in contexts involving few and large beneficiaries of the environmental services, such as hydroelectric companies or municipalities.

These alternative uses of agricultural lands create a terrific opportunity for policy innovation, in particular by repurposing farm subsidies. OECD (2020) estimates that across 54 countries which it tracks, transfers to the agricultural sector averaged US$708 billion/year for 2017–2019, of which fully US$425 billion was budgetary spending, with the rest coming through market-price support programs. Three-quarters of the amount goes to individual producers, mostly in forms that distort markets. Eliminating massive subsidies seems a political non-starter in most or all of the countries where they are large. But it may be politically feasible to transition from uncoupled farm payments or expensive market price supports to subsidies for farmer capital investments in renewable energy structures, in PES, in land conversion for GHG sequestration, and in the digital technologies—and supporting market infrastructure—necessary to monetize those energy and environmental services. A more forward-looking approach to the use of politically explosive farm subsidies can safeguard rural communities for the coming future when de-agrarianized production methods begin undercutting rural economies heavily dependent on conventional agricultural commodity production.

Facilitating land conversion from agriculture will also require action regarding land use rules. Secure land tenure is essential to induce investment in GHG mitigation in trees, soils, or cover crops, much less in installation of wind turbines or solar panel arrays. Concerted efforts will be necessary to overcome commonplace local opposition (e.g., "Not In My Backyard!" NIMBYism) regarding the siting of wind turbines, solar panels, protected areas for predators, etc. These are delicate processes but essential to transitioning rural landscapes.

Supply Chain Innovations

Purposeful changes are needed for AVCs that extend from the farm through to the consumer and end-of-life material considerations. We emphasize six key facets needing—and increasingly getting—attention from food and beverage companies, ingredient suppliers, global governance structures, non-governmental organizations, wholesale and retail operations, and national policy makers.

The first surrounds value chain certification standards. Many claims about a product's environmental, ethical, or healthful properties—its credence attributes—cannot be verified directly by purchase or consumption (Barrett 2021). This makes it difficult for firms to monetize the value of desirable product characteristics and, thus, to use market mechanisms to incentivize such innovations. In several regions, government agencies, like the US Food and Drug Administration and the European Food Safety Authority (EFSA), regulate heath claims based on scientific evidence on the label. Regarding environmental sustainability of products or services, a large European initiative is now evaluating a label called Product Environmental Footprint, which builds on prior prototypes and studies (e.g., Leach et al. 2016). Companies like Unilever propose to explicitly report associated GHG emissions on the packaging of tens of thousands of products. The International Organization for Standardization (ISO) standards for carbon labelling require a full life-cycle analysis and third-party verification, the cost of which poses a potential hurdle for small- and medium-sized companies and for mass labelling. A future area of innovation may focus on ways to reduce the cost of these assessments and potentially automate for large numbers of varied products. However, it also seems challenging to agree on a representative and simple sustainability indicator that consumers understand, that is widely adopted and recognized by different stakeholders, and that covers the various dimensions needed (Chaudhary et al. 2018; Chen et al. 2019). For example, nutrition and linked health impacts are essential, but are not considered in the Product Environmental Footprint.

We need accelerated convergence of food and ingredient supply chain certification schemes on key performance measures that catalyze the UN SDGs and an expanded set of Science Based Targets (SBTs).[15] Success in leap-frogging beyond the existing meta-system of certification standards will reflect four distinct refinements:

[15] SBTs are widely accepted targets voluntarily agreed by companies to set a clearly defined pathway towards medium- to longer-run goals. To date, these have focused almost exclusively on reducing GHG emissions so as to mitigate climate change. See https://sciencebasedtargets.org/ for further detail.

- unifying KPMs for social, economic, and environmental aspects;
- clarity and transparency for supply chain participants from consumer-to-the-farm around a single set of KPMs;
- a continuous improvement ecosystem of measures, protocols, resources, and consumer communication; and
- an easily adopted framework for governments to focus sustainable food system policy development and support structures.

The emergence of harmonized standards and associated measures, with traceable, trackable, scrapable product-level data, could ultimately supplant costly third-party certification if individual companies' and industries' compliance becomes fully transparent and independently verifiable by government regulators and consumer groups.

In the near term, KPMs within certification schemes need to evolve to reliably capture key indicators (discussed below) that directly support the SDGs and SBTs. In order to deliver broad-based change, in particular with small- and medium-sized value chain participants, certification schemes require reciprocity and KPM convergence so as not to unfairly burden upstream players, especially small-holder farmers (Loconto and Dankers 2014). Certifications are to be built around principles of continuous improvement rather than either achievement of a standard that is then passively maintained, or such a high entry hurdle that it dissuades parties from initiating the scheme (Blackman and Rivera 2011). KPMs must be supported through nonmanipulable tracking and traceability technologies of the sort we discuss below.

Certification frameworks would be best linked to relevant objectives and indicators. When a certification process is established, it brings an ecosystem of frameworks that support measurement, verification, transparency, capability building, and communication (e.g., third-party certification bodies, technical panels to oversee measures, standards and technical resources developed for user networks, etc.).

Designing for an ecosystem of measures, protocols, resources, and consumer communication acknowledges the ongoing infrastructure and support required to drive long-term continuous improvement across KPMs. Protocols and resources are the domain of value chain participants, certification bodies, auditors, civil society, and, where possible, government actors who all come together pre-competitively to build the elements of the scheme and a means of continuous improvement by establishing protocols, independent and verified auditing, best-practice sharing, training, and capability building.

Certification schemes create clear expectations about standards and compliance, thereby generating credibility and consumer trust at point of purchase. Such trust is essential to monetize latent consumer willingness to pay for credence attributes and thereby internalize key climate, environmental, and social externalities generated throughout the AVC. Standards must also be easily and reliably communicated to consumers in simple, easy-to-understand messaging and icons or logos that indicate verified performance and transparency. Avoidance of logo proliferation is important, however, so as not to sow confusion among consumers. Furthermore, while larger producers may be capable of achieving and maintaining multiple certifications, smallholders rarely can, so elimination of unique (and other high-cost) certification criteria and mutual recognition between platforms is essential to focus the value chain on clear outcomes that make a difference while meeting the needs of a diverse array of consumers and producers.

This requires more cooperation than presently occurs among AVC actors. It requires pre-competitive partnership of large-scale end users of food and ingredients with global governing bodies, relevant civil society organizations, existing certification bodies, suppliers, and implementation partners. While progressive enterprises should be encouraged to pilot innovative methods, in order to generate scalable, trusted methods, such experiments must be done in the spirit of shared learning to be incorporated into the meta-system to benefit all parties. This will also require a modular approach reflecting the heterogeneity of underlying AFSs and starting points.

The second key supply chain innovation space, closely related to certification, concerns consumer transparency. This has a robust foundation in food and beverage nutritional labeling that is currently coordinated through Codex Alimentarius, a collection of internationally adopted food standards and related texts jointly supervised by FAO and the World Health Organization (WHO). The Codex legacy of fact-based disclosure must be extended to key indicators that support the UN SDGs and SBTs, and HERS objectives more broadly (Box 6). The potential consumer and social benefits from food labeling are considerable but often limited by the imperfect information available to purchasers, along with consumer behavioral biases (Sunstein, in print).

Box 6: Towards fact-based sustainability labelling

In the early 1970s, consumer transparency in foods and beverages was improved with refinement of a standardized nutrition-facts table printed on pre-packaged foods. Its development was initially supported by the US Food and Drug Administration and has evolved to governance and technical oversight by Codex Alimentarius, a UN body under joint WHO and FAO direction (Codex Alimentarius 2017). Some version of the nutrition facts label is mandatory for packaged foods in 58 countries and voluntary in another 19 (EUFIC 2016). This adoption rate, with technical rigor and coordination through a central governance body, supports global consistency for package labels. The precise regulation of labelling compliance is carried out at the country level. This system supports consumer confidence in food and beverage nutritional disclosures, empowering consumers to make reliable inter-product assessments when making purchasing choices and enabling companies to elicit revenue from consumer valuation of improved nutritional content.

These elements—central governance, technical rigor based on agreed and credible measures, local enforcement, and transparent and fact-based disclosure focused at individual consumers—set a precedent relevant to the challenge of communicating other HERS-related product attributes to consumers at the point of purchase. Lessons from the nutrition-facts label experience can inform development and consumer-directed communications of sustainability key performance measures that support the SDGs and SBTs (Leach et al. 2016). Such labelling regimes can activate latent consumer valuation of product credence attributes, thereby internalizing spillover effects and generating revenues necessary to cover the costs of improving environmental, equity, and health outcomes associated with specific food products. With credible measures and certified quantification, food and beverage markets can compete on a more equal footing, transcending greenwashing concerns with enhanced transparency, benefiting a range of AVC participants, and thereby advancing fruitful product and process innovations.

Transparency must also include disclosure of provenance for ingredients that, when combined with nutritional and third-party verified credence characteristics, paves the way to consumer trust and informed decision making. Here again, emergent technologies to enable nonmanipulable tracking and traceability become important. A number of promising initiatives are in early stages, such as the European Union's Product Environmental Footprint pilots or Unilever's GHG labeling initiative, as described above. **The potential to create universally recognized and respected labels, backed by reliable standards and testing, that earn and maintain consumer and regulator trust opens up exciting opportunities** to induce beneficial innovation by incentivizing it for AVC firms.

The third class of promising supply chain innovations are in food processing and are based on different (1) operations (*structuring, conversion, stabilization*, and *separation*), (2) processes (physical: thermal, electro-magnetic, and mechanical; and biotechnological), or (3) product property scales (nano, micro, meso, and macro scale). Especially due to emerging needs for urban food production, small-scale modular factories (Mathys 2018) for processing close to production or urban environments (e.g., megacities) are receiving more attention, as improved energy and water delivery technologies and robotization reduce economies of scale. Focused process synthesis approaches (Westerberg 2004) to adapt new ingredients (e.g., plant-based ingredients in place of animal-sourced ones) and desired final product attributes, (e.g., preferred organoleptic properties) are especially crucial. These process-synthesis approaches can deliver innovative product property scales, from nano to macro, not only for mimicking meat structures, from myofibrils (meat fibers) to final structured product, but also for enabling emerging single-cell and plant-based protein-rich products with new structures and ingredients to deliver preferred organoleptic properties such as superior taste, nutrition, and mouth feeling.

Emerging *structuring/conversion* processes—such as advanced high-moisture extrusion, 3D printing, shear cell technology, spinning, and stem cell techniques (i.e. for lab meat)—enable innovative meat substitutes or new protein-rich products based on more sustainable proteins (Dekkers et al. 2018). New ways of food *stabilization*/preservation based on the Multi-Hurdle Technology (MHT) (Leistner and Gorris 1995) concept deliver safe food with higher qualities, including emerging physico-chemical hurdles to reduce water activity, such as solar driers combined with moisture control that allow smallholders to preserve fruits and vegetables; and physical hurdles with less thermal intensity, such as ultra-short thermal processes in milli seconds; high pressure (isostatic and dynamic), pulsed electric fields; low- or high-energy electron beam; or cold atmospheric pressure plasma processing (Reineke and Mathys 2020).

High throughput *separation* processes can clean/sanitize contaminated commodities (e.g. mycotoxin contaminated grains).[16] Building out the capability for precision fermentation or single cell biorefineries of lipids (e.g., polyunsaturated fatty acids), precision or cellular proteins, and carbohydrates (e.g., exopolysaccharides) with cascade-wise extraction of, first, functional and then, bulk ingredients will help to reduce AFSs' land and water footprint when done in ways that boost carbon sequestration and biodiversity. Multi-processing biorefineries will emerge to integrate various process innovations, much as already exist for grains, sugar, etc.

WE EXPECT THAT PENALTIES AND INCENTIVES WILL BOTH BE NEEDED TO REMOVE PIGMENTS, ADDITIVES, AND POLYMERS THAT MAKE RECYCLING UNECONOMICAL CURRENTLY.

The fourth class of promising supply chain innovations concern packaging. Ultra-processed foods, in particular, are not only associated with adverse health outcomes, they also use extensive packaging that has serious disposal impacts

[16] Buhler provides a nice example: https://digital.buhlergroup.com/lumovision/.

worldwide, ranging from toxic compounds, to hazards to wildlife, to solid waste (Seferidi et al. 2020). Besides reduction of packaging materials, the transition from single-use plastics/virgin abiotic material to 100 percent recyclable, biodegradable, or compostable materials must quickly become the norm worldwide. This will require investment and legislation that supports sufficient recycling infrastructure (open loop, closed loop, and chemical) to match the packaging material being used and behaviors through the life cycle to recapture molecules for reuse. **We expect that penalties and incentives will both be needed to remove pigments, additives, and polymers that make recycling uneconomical currently**. Beyond enablement of recycling and renewable resource utilization, there remains a significant gap in available technologies via monomers and compostable organic packaging materials that feasibly deliver required barrier properties (oxygen, water vapor, light, aroma, etc.) or the technologies may not have the right physical properties (personal communication Prof. Selçuk Yildirim, ZHAW, Switzerland). Many activities in this space are running in industrial environments and are not published, hence the status quo is not quite clear. Recent developments in food-processing multinationals demonstrate the increasing focus on recyclable, biodegradable, or compostable packaging materials, for example, the 2019 establishment of the new Nestlé Institute of Packaging Sciences.

Rapid advances in waste management represent the fifth promising supply chain innovation space. In general, the waste management hierarchy indicates an order of preference for action to reduce and manage waste.[17] First comes prevention: preventing and reducing waste generation. Next comes reuse and preparation for reuse, giving the products a second life before they become waste. The next priority is recycling, consisting of any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. This is followed by energy recovery, such as waste incineration that upgrades less inefficient incinerators. The lowest priority is disposal of waste, be it landfilling, incineration, pyrolysis, gasification, or other finalist solutions. This hierarchy is rapidly winning acceptance by local to national governments and is being incorporated into standard operating practices at successful companies (Hansen et al. 2002; UNEP 2013).

[17] According to FAO, Food loss is the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retailers, food service providers, and consumers. Food waste refers to the decrease in the quantity or quality of food resulting from decisions and actions by retailers, food service providers, and consumers.

Food waste and losses occur at different points in the value chain, each requiring different innovations. Many require behavioral change more than scientific or engineering advances. For example, according to the Rockefeller Foundation Report "ReFED: The Roadmap to Reduce US Food Waste," major impacts for food waste and loss reduction in the US are linked to awareness, traceability, and transparency (ReFED 2016). Food loss reduction strategies in low-income regions are complex and involve, for example, awareness-raising combined with training and organization of smallholders, and improved storage and preservation capacities (e.g. for fruits and vegetables), distribution, and logistics (Cattaneo et al. 2021). Awareness, traceability, and transparency are also needed here. A recent global assessment of nutritional and environmental losses embedded in food waste could serve as a base for tracking potential intervention impacts, supporting policies or investments, and engaging various stakeholders within the value chain (Chen et al. 2020).

Some further technical-focused solutions might include (1) distribution and storage of higher quality and fresher foods, stabilized/preserved by emerging MHT concepts at ambient temperatures instead of energetic and partially challenging cold chains; (2) building out uses and upcycling of AVC by-products, for example, providing ingredients for brewers, distillers, and manufacturers; or (3) technology for digitally customizing individual serving/portion sizes in away-from-home dining.

As mentioned above, the sustainability issues related to fertilizer use and soil depletion can be addressed by innovations at the nexus of sanitation, energy, and soil health. A range of possibilities are being explored to deal with organic byproducts of animal agriculture, industry, and human digestion. One set of options entails anerobic digester technologies that can be introduced into both private AVCs that are generating waste products that cannot be upcycled, and into urban settings that generate an estimated 2.8 billion metric tons of organic waste annually. Outputs from an anerobic digester can support local electricity production, and the solids can be combined with aqueous ammonia to produce an organic fertilizer for use by local farmers. The precision fermentation model would also contribute to more local production and less generated food waste.

The final promising innovation space in supply chains relates to initiatives to enhance value chain resilience to shocks. Some of those innovations are technological. For example, MHTs will support resiliency as they increase the ability to store and also reduce food waste. Others are less innovations than investments to reinforce or relocate key transport infrastructure. Sea level rise due to global warming poses an especially grave threat because seaports are overwhelmingly located in low-lying coastal zones and delta regions.[18] **Sea level rise will affect ports through incremental, as well as catastrophic, flooding that damages infrastructure and cargo**.[19] In 2005, Hurricane Katrina halted shipping at three Gulf ports in the US, which together handle 45 percent of the nation's agricultural goods and resulted in a 3 percent increase in food prices temporarily (Drabenstott and Henderson 2005). Recent studies reinforce the magnitude of sea level rises and the irreversible impacts of ice sheet loss on coastal populations and infrastructure (Garbe et al. 2020). Ports around the globe are under-prepared to cope with these challenges. A survey of seaports that collectively account for over 16 percent of global seaborne trade reveals that although 70 percent of the respondents have, or plan to have, emergency response measures, about 40 percent do not have, or do not plan to have, any vulnerability assessments, and 41 percent have yet to conduct any identification and evaluation of potential adaptation measures (Asariotis et al. 2018). The survey also reports that instead of soft adaptation strategies, such as changes in operations and management, respondent ports mainly chose hard engineering measures as the main strategy with an average cost of US$127.3 million.

The projected effects of sea level rise are quite spatially concentrated. Eight Asian countries—Bangladesh, China, India, Indonesia, Japan, Thailand, the Philippines, and Vietnam—are home to more than 70 percent of the world population now occupying land vulnerable to sea level rise (Kulp and Strauss 2019). Indonesia's recent decision to move its capital from a swelling and sinking coastal city, Jakarta, to eastern Borneo is partly a direct response to the perils posed by sea level rise. Bangladesh and Vietnam are especially vulnerable, as roughly one-third of each country's population will permanently fall below high tide line by 2100, even with a significant reduction in emissions. The most catastrophic cases will obviously be low-lying small island states, whose very existence may be imperiled by rising seas.

Singapore provides an illuminating example of how nations are adapting to various threats posed by AVC disruptions. Currently, Singapore produces only 10

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[18] In addition, an estimated 80 airports worldwide could be underwater with the projected one-meter-sea level rise by 2100 under the IPCC (2019) business-as-usual scenario, including some of the busiest in the world, for example, Amsterdam Schiphol (Huang and Maghsadi 2020).

[19] Potential tidal modulation can also cause sedimentation, forcing expensive dredging in navigation channels and changes in operational timetables (Asariotis et al. 2018; Stenek et al. 2011; Nicholls et al. 2008; Admiraal 2011; Becker et al. 2013).

percent of the food its population consumes. Historically, this has worked fine, as inexpensive imports reliably supplied the island nation's food needs. Even before the COVID-19 pandemic threatened imports due to commercial freight shutdowns and export bans imposed by some exporters, thus making Singapore's low self-supply rate a vulnerability, the government was committed to substantially increasing its self-provisioning of food so as to reduce vulnerability to short-term disruptions arising from any of a host of shocks (Zulkifli 2020). The threats posed to Singapore's port infrastructure by sea level rise merely aggravate the looming problem. The nation has now made it a strategic priority to increase domestic production to satisfy 30 percent of its nutritional needs by 2030. This is fueling rapid upscaling of investments in CEA, circular feeds, and other forms of de-agrarianized food and feed production, given the scarcity of land on the island, as well as advances in food loss and waste recovery and in food processing so as to triple domestic supply within a decade.

Health and Nutrition Innovations

Important downstream innovations show particular promise in advancing the healthy diets objective, but that may also help advance other AFS goals. We coarsely lump these into three categories: new nutritious foods, nutritious supply chain innovations, and new frontiers in human nutrition.

New technologies are emerging to produce and formulate new nutritious foods or new variations of foods to ensure that the food supply is providing healthier foods while potentially, at the same time, addressing climate change and environmental concerns, as well as issues of equity and inclusion in food distribution. One such technology is 3D printing, which can make a three-dimensional object based on layer-by-layer deposition following computer aided design (Yang et al. 2017). With 3D printing, ingredients can be mixed and processed into intricate designs and shapes, introducing new flavors and textures that cannot be currently formulated by regular cooking processes. **3D printing has the potential to support personalized food manufacturing through home scale production**. Questions, nonetheless, remain about consumer acceptance of 3D printed foods. And it is unclear whether 3D printing would promote healthier diets or reduce food loss and waste.

Genetic modification (GM) of organisms is another technology that has grown through a range of advances in genetics and genomics that enable the change, removal, or addition of genes to crops and livestock that are believed beneficial for one reason or another. The earliest GM agri-food technologies promoted shelf-stability in tomatoes, stimulated lactation in cows, obviated the slaughter of calves in extracting rennet for cheesemaking, and especially introduced pest and/or herbicide resistance to field crops like canola, cotton, maize, and soy. These initial ventures were largely aimed at boosting or stabilizing production (Qaim 2016). **Second generation GM agri-food innovations increasingly address nutrition issues—such as micronutrient deficiencies—that remain prevalent in too many** LMICs (Glass and Fanzo 2017). To address micronutrient deficiencies, staple crops such as maize, rice, and wheat could either use GM technology or conventional or accelerated breeding to increase the nutritional content of vitamin A, zinc, or iron, for example, through an innovation known as biofortification (Bouis and Saltzman 2017; CAST 2020). One such example of a nutrient-rich GM crop is the controversial golden rice in which beta-carotene was built into the rice grain to produce a vitamin A—rich rice product (Regis 2019; Stokstad 2019).

The alternative proteins discussed above open up a range of prospective nutrition innovations. Precision protein (also known as single cell protein or microbial protein) is produced by a microbe (algae, fungi, yeast, or bacteria). The microbe may, or may not, be bioengineered, and the product may be secreted from the organism or processed within the cell. Cellular proteins (also known as cultured or tissue engineered meat) are produced as multi-cellular animal tissues that maintain cell structure through production. No matter the source method, plant proteins—which are almost always processed in some way—can be easily combined in various ways. The nutritional content of cultured meat may not be a significant concern because the nutritional composition of these foods can be modified, enriched, and fortified in the lab to match the foods found naturally (Sergelidis 2019). But challenges remain. Will consumers accept these novel foods (Bryant and Barnett 2019)? History shows that consumers are often suspicious of unnatural foods, at least initially (Chriki and Hocquette 2020). Other concerns include cost, taste, sustainability, and safety.

Reformulation is the process of altering a food or beverage product's processing or composition to improve the product's health profile or to reduce the content of harmful nutrients or ingredients (Scott et al. 2017). Reformulation encompasses both removing negative ingredients and nutrients, as well as adding positive ones to foods ranging from minimally to highly processed foods. Reformulation may be undertaken for reasons unrelated to better public health outcomes via improved nutrition. Companies can, and do, reformulate products for a variety of other reasons, including to increase nutrient density; to improve shelf-life, safety, and taste; to reduce costs; and to otherwise improve profitability (Box 7).

Box 7: Reformulation, fortification, and functionalization—incentivizing old innovations

There has been increased attention given to the health impacts of highly processed foods that are high in salt, added sugar, saturated and trans fats, and energy density, and low in fiber, protein, and micronutrients, and that also contribute to, and are associated with, overweight, obesity, and non-communicable diseases (Vandevijvere et al. 2019; Monteiro et al. 2013; Baker and Friel 2016; Baker et al. 2020; Hall, n.d.). Sub-optimal dietary outcomes have stimulated governmental nutrition policies to strive to reduce the intake of salt, added sugar, and unhealthy fats. Alongside promoting consumption of fresh nutritious foods (e.g., fruits, vegetables, and whole grains), the **reformulation, fortification, or functionalization** of processed foods may help improve diets in every food system. Can reduced processing of food—such as grinding, milling, and the removal of key nutrients—to promote more whole foods decrease the need to add back nutrients post-processing and reduce environmental footprints of the process overall (Seferidi et al. 2020)? The innovations in this space are less around food science than around aligning incentives.

Reformulation of foods can remove negative nutrients and/or add positive nutrients. Currently, it consists mainly of reducing the amount of salt, added sugar, saturated and trans fats, and the energy density in processed foods, largely to produce niche products to expand the range of consumer choice (Buttriss 2013). Reformulation can also increase healthy components, such as fiber, protein, micronutrients, or phytochemicals. **Fortification** adds essential vitamins and minerals to commonly consumed foods such as maize flour, edible oil, rice, salt, and wheat flour. It can also replace micronutrients lost during processing, such as with cereals, or address micronutrient deficiencies in the population, as with iodized salt (Das et al. 2019; Salam et al. 2019). **Functionalization** involves adding other beneficial ingredients that are specifically targeted to improve health (phytochemicals, pro-biotics, etc.).

While the main research focusing on reformulation, fortification, and/or functionalization concerns these processes' potential to improve nutrition and health, the main current industrial practices are for other, commercial purposes: decreasing costs, meeting changing consumer preferences, tapping into new consumer markets to boost sales or the company's public image, improving food safety and preservation, and/or complying with government regulations, where they exist).

Inducing more reformulation using existing technologies to promote healthy diets likely requires shifting incentives through labeling requirements, taxes, and/or regulatory constraints. Clear consumer signaling through labeling can incentivize companies to reformulate, particularly if labels carry warnings. Simple, easy-to-interpret front-of-pack labels that include stars, traffic lights, or other assessments of nutrition and health are increasingly effective and used in Chile, Australia, New Zealand, and the US, among others (Reyes et al. 2019; Chantal et al. 2017; Hersey et al. 2013; Jones et al. 2019). Companies reformulate products in order to avoid a low rating or a warning label (Vandevijvere and Vanderlee 2019).

So-called "sin taxes" are another tool. National and local taxes on sugar-sweetened beverages (SSB) and other energy-dense foods have been introduced in several countries (Hagenaars). In Mexico, Saudi Arabia, and Chile, SSB taxes were associated with an 8–24 percent reduction in purchases (Taillie et al. 2020). Sin taxes often face strenuous corporate resistance, however (Sainsbury et al. 2020).

National bans of certain ingredients (e.g., trans fats or salt) or requirements of nutrients in specific food vehicles (e.g., fortification of flours, oil, or salt) also shift industry incentives to adjust the product portfolio (Fanzo and McLaren 2020). Where private industry standards cannot converge around beneficial practices—as in the case of salt iodization in the US, for example—government regulatory standards may be necessary.

Ultimately, food industry actors need incentives—positive or negative—to reformulate foods not only in response to consumer preferences that can be manipulated through marketing, but equally, to improve consumer nutrition and health, as well as environmental sustainability in the face of the climate crisis. The food industry responds to new demands to make premium or superior products, as well as continual demands to make lower-cost products.

Once food moves through supply chains, innovations attempt to maintain or improve quality and ensure those foods are accessible and affordable. For at least 3 billion people, healthy foods remain unaffordable (Hirvonen et al. 2020; Headey and Alderman 2019; Bai et al. 2020; FAO 2020). The bitter irony is that affordable, healthy diets are especially inaccessible to the rural poor, who are most likely to work in AFSs. For example, 63–76 percent of India's rural poor could not afford a recommended diet in 2011 (Raghunathan et al. 2020). Globally, Bai et al. (2020) find that the minimum cost of a nutritious diet relative to household per capita expenditures falls with per capita income, access to electricity, and proximity to a city.

Food consumption can be influenced by ensuring nutritious foods are cheaper and unhealthy foods are more expensive (Eyles et al. 2012; Thow et al. 2014). **Taxes and subsidies can be used to shape prices and change dietary intake**. For example, taxes on SSBs can lead to a 20–50 percent reduction in consumption, while the subsidies for fruits and vegetables can lead to a 10–30 percent increase in consumption (Thow et al. 2014). However, taxes can be regressive, imposing greater economic burdens on the poor than on the wealthy. Combining taxes with healthy food subsidies—which have been far less common—could be one mechanism to mitigate the regressivity by allowing for populations to switch to healthier products without additional costs (Thow et al. 2010).

Nonmanipulable tracking and traceability using molecular markers, biomarkers, micro sensors, regulation, etc., can also improve food safety and help producers and intermediaries capture consumer valuation of foods' credence attributes. However, significant challenges and technical barriers must still be overcome. Food safety tracking and traceability systems are probably one of the best developed solutions in this domain in most high-income countries. However, much of the Global South still lacks sufficient safety tracking and traceability, with serious consequences, such as outbreaks of pathogenic bacteria or viruses, and chemical contaminations.

Block chain technology in agriculture and food supply chains has gained much attention recently. Is this a solution for nonmanipulable traceability? Significant challenges with this still-emerging technology exist around accessibility, governance, technical aspects (e.g., energy demands), policies, and regulatory frameworks (Kamilaris et al. 2019; Behnke and Janssen 2020). As with every innovation, we need to maximize the technology readiness level up to 9 (i.e., the actual system proven in an operational environment) before reaching strong conclusions, and we must learn from the ongoing innovation cycle.

Precision or personalized nutrition (PN) is an approach to addressing current nutrition problems using large quantities of detailed and multidimensional metabolic and health data to better understand the range of how human metabolism responds to diet. PN relies on a wide range of tools, including genomics, metabolomics, microbiomics, phenotyping, high-throughput analytical chemistry techniques, longitudinal tracking using body sensors, informatics, data science, and education and behavioral interventions to arrive at highly personalized and targeted dietary guidance and interventions (O'Sullivan et al. 2018).

Although many studies have been performed to identify genetic factors that explain the variability in metabolic response to specific diets, most findings are still relatively far from translatable for guidance. However, there are examples of findings that have already translated into guidance—including hypolactasia diagnosis, the ruling out of celiac disease, or phenylketonuria screening—which have led to tailored nutritional advice (avoiding lactose, gluten, and phenylalanine-containing products for at-risk individuals) based on genetics (de Toro-Martín et al. 2017).

Individualized approaches to PN remain expensive, though, and therefore may not be feasible in all settings due to budget constraints. Cost is a big reason why PN has thus far been targeted mainly to high-income environments, where individuals face very different nutritional challenges than do those in resource-poor settings. Moreover, **PN is not a substitute for public health infrastructure addressing underlying social, political, and economic inequities that are known drivers of population health outcomes**. There is much work to do in removing existing barriers (social, economic, political) to adequate diets. PN can fine tune once barriers are removed. Global populations may be diverse, so the call for diversified approaches to addressing diet-driven health problems makes sense on its face. But are individual differences in responses to diets really a significant driver of the global burden of diet-related disease? Thus far there is insufficient evidence that genotype-specific recommendations from direct-to-consumer genetic testing companies perform any better than "one-size-fits-all" recommendations (Loos 2019). For example, one recent study attempting to predict who would respond to dietary supplements of omega-3 fatty acids did not perform well out of sample (Marcotte et al. 2019). A second study examining the effects of dietary linoleic acid found an effect (Lankinen et al. 2019), but the magnitude was too small to be of use in precision nutrition (de Roos et al. 2019). While there is significant enthusiasm for PN-based methods, we do not yet see this as a high-potential area.

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