The State of Agri-Food Systems and Agri-Food Value Chains in 2020

One might reasonably invoke Dickens in describing AFSs and AVCs today: "it was the best of times, it was the worst of times." **There has been indisputable progress over the past hundred years, even the past decade. But there has also been backsliding, and contemporary AFSs are utterly unsustainable**, with massive, adverse spillover effects on the natural environment, public health, and social justice. Optimists and pessimists can each find support for their views in the data on contemporary AFSs.[1]

Remarkable agricultural productivity gains occurred over the past century, as exemplified by gains in maize (corn) yields in the United States (Fig. 1). But the agri-food research and development (R&D) that yielded these gains has been heavily concentrated in a small number of crops, primarily starchy cereals (e.g., maize, rice, and wheat), roots and tubers (e.g., potatoes), and livestock. This has led to declining relative prices of these staple commodities as compared to nutrient-rich fruits, legumes, nuts, and vegetables that have received far less R&D investment and which few countries produce in quantities sufficient to meet their populations' dietary requirements (Pingali 2012; Mason-D'Croz et al. 2019; Haddad 2020; Sanchez 2020).

Moreover, these productivity gains have also varied sharply across regions (Fuglie et al. 2020) and food system types (Fig. 2). We see variation in the magnitude of change, shown as longer time sequences in Fig. 2. Productivity gains in the world's industrial and consolidated AFSs have outpaced those of the rural and

[1] This is apparent in the recently released Food Systems Dashboard, which provides the most up-to-date data available on over 150 different indicators describing food systems at country, regional, and global scales (Fanzo et al. 2020).

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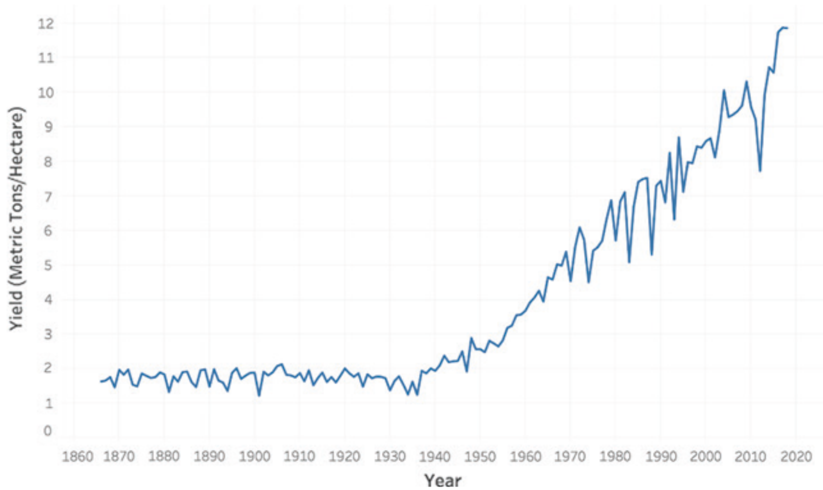


Fig. 1 Average maize (corn) yields in the United States, 1866–2014, in metric tons/hectare (*Source* United States Department of Agriculture and UN FAOSTAT)

traditional systems. Moreover, differences exist not only in the magnitude of productivity gains over time but also in their biases in favor of laborers or land owners. In rural and traditional systems (mostly the poorest regions of sub-Saharan Africa and South Asia), advances in improved germplasm, irrigation, etc., have mainly favored gains in land productivity (i.e., yield growth) that mainly benefit landowners. This is reflected in expansion curves that climb more steeply than the dashed, diagonal lines representing constant land/labor ratios in primary agricultural production. Conversely, labor productivity growth (e.g., from labor-saving machinery and agrochemicals) that chiefly rewards workers has outpaced land productivity growth in industrial and consolidated AFSs. Poverty remains both more pervasive and deeper in rural areas than urban ones in most of the world, coincident with the places where people depend most heavily on AVCs for their livelihoods as farmers, farm workers, transporters, meatpackers, etc.

Figure 2 also plainly reveals the stark difference in productivity across AFSs. Agricultural output per unit land in production is severalfold higher in industrialized systems than in traditional ones—reflecting the crop yield gaps on which so much of the agricultural sciences community focuses. But these gaps pale in comparison to those in labor productivity. Agricultural output per adult employed in agriculture is nearly two orders of magnitude greater in the industrialized

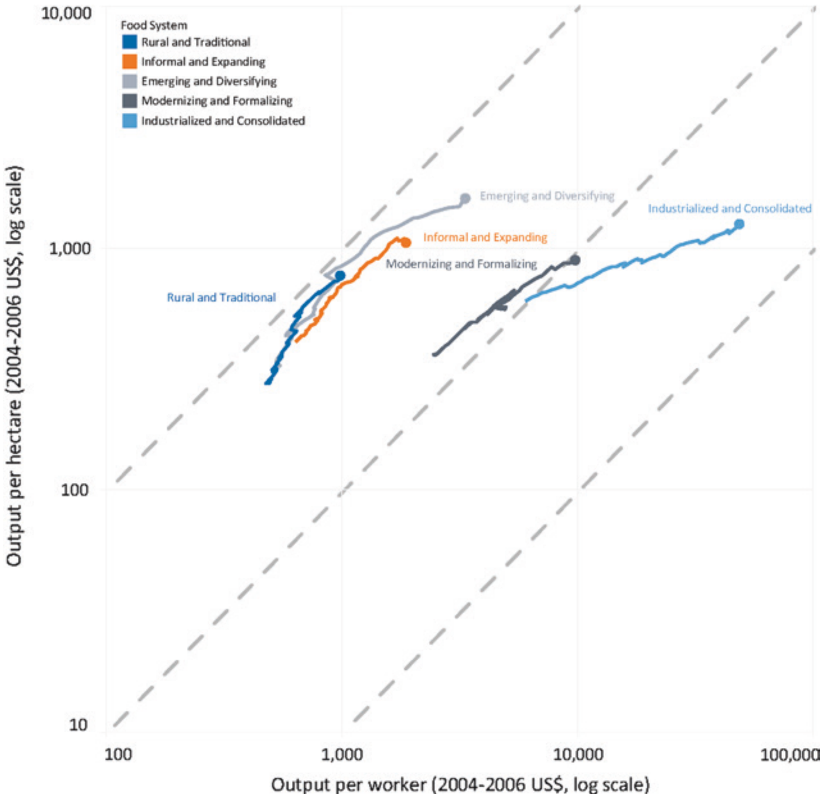


Fig. 2 Trends in agricultural land and labor productivity, 1961–2016, by food system type. Colored lines show changes in productivity over time, from 1961 through 2016. Output is in 2004–2006 international dollars. Labor reflects number of adults employed in agriculture, and land as agricultural land in rainfed equivalent (*Data source* USDA-ERS International Agricultural Productivity Database; figure adapted from Fuglie et al. 2020)

systems than in the traditional ones. This stark difference is a central reason for radical differences in living standards across the globe. Many technologies and practices already widely in use could significantly close those gaps,[2] but for

[2]As but one example, on-farm experiments in Nigeria generated dramatic yield gains in cassava simply through generous fertilizer application (Adiele et al. 2020).

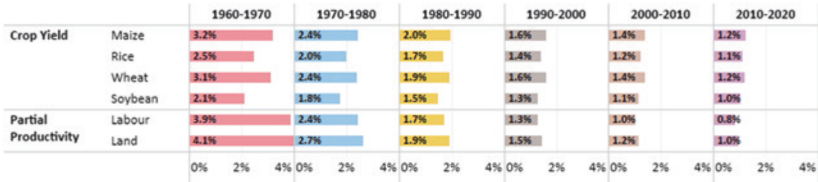


Fig. 3 Global crop yield, labor, and land productivity annualized growth rates, 1960–2020. Estimated as compound annual growth rates per decade, based on regressions of global data (*Data sources* FAOSTAT for crop yields and USDA-ERA International Agricultural Productivity Database for partial productivity measures)

myriad reasons are not widely available or adopted in poor rural areas in the low-income world. Closing existing productivity gaps using extant knowledge could help advance equity and healthy diets goals quickly, but too often with significant environmental and climate sustainability tradeoffs.

The rate of agricultural productivity growth has slowed markedly over the last generation, however (Alston et al. 2009; Fuglie et al. 2020, Fig. 3). In addition, agri-food R&D has increasingly shifted to the private sector. Private R&D now accounts for more than two-thirds of total agricultural R&D spending in both China and the US (Chai et al. 2019). One result is that intellectual property rights (e.g., patents) are increasingly likely to impede affordable access to, and adaptation of, new discoveries. Partly as a result, the R&D cost per unit productivity gain has also been rising rapidly (Bloom et al. 2020). The gap between high- and low-income country agri-food R&D has been growing (Pardey et al. 2016). Meanwhile, anthropogenic climate change has countered some of the favorable impacts of technological change, reducing global agricultural total factor productivity growth by 21 percent since 1961, equivalent to losing roughly a decade's productivity growth (Ortiz-Bobea et al. 2020).

Gains in on-farm productivity have helped propel growth downstream in food processing and distribution. AVCs continue to dominate employment, especially in poorer countries. The agricultural share of an economy's labor force steadily declines as part of the inevitable process of structural transformation, in which workers migrate from agriculture to other sectors even as agricultural output grows and despite agriculture's greater labor-intensity than other economic sectors (Barrett et al. 2017; Mellor 2017). But growth in downstream portions of AVCs accelerates at the same time. Today, employment in the post-harvest segments of AVCs dwarfs on-farm jobs and is growing globally, even by a factor of ten in Sub-Saharan Africa (Thurlow 2020; Yi et al. 2021; Dolislager et al. 2021).

While AVCs employ more people worldwide than any other sector—more than 1.3 billion (ILO 2015)—**AVC jobs are also more poorly compensated, dangerous, and precarious than those in any other sector save mining, and more prone to child, forced, and unsafe labor than those in any other sector but textiles**. The International Labour Organization (ILO) reports that agricultural workers account for approximately half of all fatal occupational accidents annually (ILO 2017). Marginalization and group-based discrimination—against women, ethnic, racial, or religious groups, etc.—is pervasive in AVCs. This marginalization typically reflects broader systemic discrimination within the societies of which AVCs are a part. These features intersect, as economic desperation and sociopolitical marginalization drive under-resourced groups to take on more perilous and poorly compensated work. The concentration of marginalized populations in AVC employment that is more dangerous and less remunerative than employment in other sectors thus magnifies broader societal problems within AFSs. Partly as a result, smallholder, farm, and AVC worker households are disproportionately likely to suffer food insecurity (FAO 2019).

Over the past 30 years, science-based advances in AFSs have boosted both food supplies and incomes. This has enabled an average of 90 million additional people each year to secure at least minimally adequate daily dietary energy intake (Fig. 4). But since 2014, and even prior to the 2020 pandemic, the number of undernourished and the prevalence of moderate and severe food insecurity have been slowly increasing, even as the total population that is food secure and receives adequate dietary energy intake has also increased (due to population growth). The undernourished increasingly concentrate in conflict-affected countries.

Past AFS advances were not designed with fragile settings in mind, thus different tools are increasingly needed to address hunger and famine concerns that are closely bound up with conflict (Barrett 2021). Today at least 3 billion people cannot afford a healthy diet, the cost of which exceeds the international poverty line, with dietary shortfalls especially concentrated among essential minerals and vitamins (FAO 2019). On the flip side, never before have more than 4.5 billion people been able to afford and consume a healthy diet (Barrett 2021)—once again, both the best of times and the worst of times.

Sustained productivity growth in AFSs drove real (i.e., inflation-adjusted) food prices to all-time lows at the turn of the millennium. And consumer food-budget shares have continued to decrease thanks to real income growth, especially in emerging markets in Africa and Asia. But real food prices both rose significantly and became more volatile over the first two decades of the twenty-first century (Fig. 5).

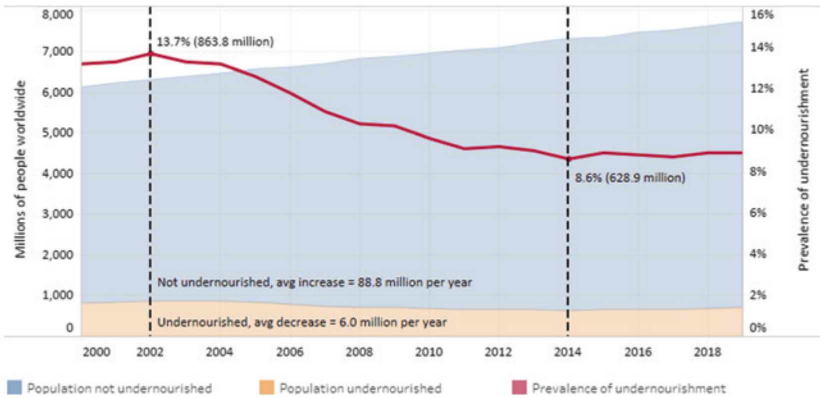


Fig. 4 Global population undernourished, 2000–2019. The colored areas reflect the number of people (not) undernourished (blue and yellow, respectively). The red line shows the global prevalence of undernourishment. The vertical dashed lines reflect the high and low points this century for prevalence, with the associated number of undernourished in parentheses (*Data source* FAOSTAT)

Ironically, the human population and income growth that now challenge sustainable management of natural systems and help foster a global overweight and obesity public health crisis have been enabled by scientific discovery that made food cheaper (Fogel 2004; Barrett 2021). **Cheaper calories and protein have naturally led to massive dietary change, and not all for the better** (Fig. 6). **Diet is now the top risk factor for morbidity and mortality globally** (GBD 2019), as per capita daily consumption of meats, empty calories (refined sugars, refined animal fats, oils, alcohol), and total calories have increased dramatically over time but also quite unevenly across country groups. As processed products[3] represent an ever-growing share of what food consumers eat, the challenges of

[3] There is no universally accepted definition of processed foods. The basic idea is that processed foods have undergone one or more changes to their natural, raw commodity state. That may involve blanching, canning, cooking, dehydrating, drying, freezing, milling, washing, etc., as well as combination in manufacturing that uses processed foods as inputs. Ultra-processed or "highly processed" foods are another ambiguous term, by which one typically means foods that have added fats, salt, or sweeteners and/or artificial colors, flavors, or preservatives, with the objective of promoting shelf stability or palatability, or preserving texture, but often at a cost of decreased healthfulness in some dimension.

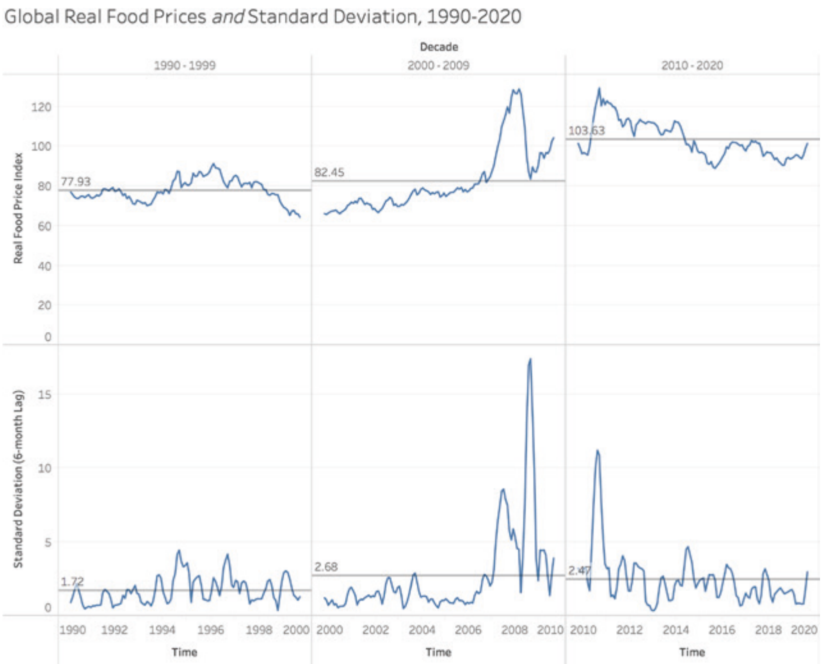


Fig. 5 Global real food prices, January 1990–July 2020 (*Data source* FAO Food Price Index)

inducing higher-quality processing and more healthy (re)formulation loom larger than ever. Not all processed foods are unhealthy, although the market and regulatory incentives presently facing food manufacturers and food service firms such as restaurants broadly favor low-cost, unhealthy refined sugars and fats.

Further, the considerable food loss and waste in today's AFSs—FAO (2019) estimates 14 percent average loss post-harvest, not including retail/consumer waste—are partly a direct function of cheap food (FAO 2019; Cattaneo et al. 2020). United Kingdom households, for example, waste the equivalent of 42 daily diets per capita per year, on average, with significant losses of key nutrients already deficient in the diet (Cooper et al. 2018).[4] Indeed, for some essential

[4] The total estimated climate impact was 20.4 million tons CO_2-equivalent per year, roughly comparable to 6.5 million round trips across the United States by car.

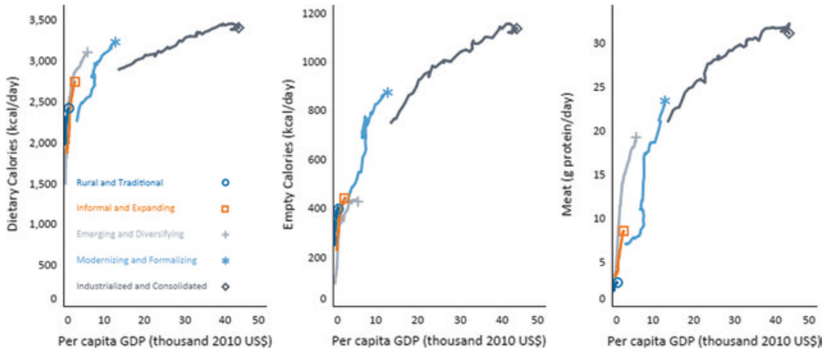


Fig. 6 Shifting food consumption patterns with income growth. Colored lines reflect 1961–2013 average consumption trends with respect to per capita gross domestic product (GDP) in thousand 2010 US dollars. Empty calories estimated as calories from sugars, sweeteners, vegetable oils, and alcohol (*Data sources* FAOSTAT for calories and protein, World Bank World Development Indicators for per capita GDP; figure adapted from Tilman and Clark 2014)

nutrients, such as calcium or folate, residual nutrient availability after accounting for global loss and waste is less than 10 percent above the recommended daily dietary requirements (Ritchie et al. 2018), implying massive prevalence of micronutrient deficiencies given the grossly inequitable distribution of healthy foods across the global population. While food loss and waste is generally considered from a "farm to fork" perspective, the disposal of post-consumption nutrients (through sanitary services or otherwise) can also be regarded as a form of waste, with enormous environmental and health consequences. "Fork to farm" approaches that recover resources for agriculture can address sanitation, health, and food security challenges, as discussed below.

Innovations in plant and animal genetics and nutrition, irrigation, mechanization, and other technologies have enabled the intensification of production to an extent that has obviated massive amounts of deforestation (Evenson and Gollin 2003; Pelletier et al. 2020; Gollin et al. 2018). But "modern agriculture" has depended heavily on dramatically increased use of inputs, including nitrogenous fertilizers made with the heavy use of petrochemicals, mined phosphates, irrigation, and pesticides (Tilman et al. 2002). Each of these input types are associated with problems and concerns related to environmental sustainability, as we discuss below.

Rural lands have massive potential to sequester carbon in soils and trees but today are a major source of avoidable GHG (i.e., CO_2, CH_4, and N_2O)

emissions.[5] Incentives based on production, global competition based on price, and long supply chains reducing transparency encourage the externalization of significant costs on the environment. This includes impacts on:

- Soils and their degradation through compaction, loss of organic carbon, salinization, and erosion (Amundson et al. 2015).
- Biodiversity, where AVCs are the biggest driver of biodiversity loss (Newbold et al. 2016; IPBES 2019).
- Water, where extraction may reduce water below the safe level for environmental integrity and deplete aquifers, as well as impact water quality through various forms of agricultural run-off. Nutrients in run-off have adverse consequences, contributing to harmful algal blooms, dead zones affecting coastal fisheries, disease outbreaks, and other environmental and human health issues (Dalin et al. 2017; Kanter et al. 2020).
- Air quality, which is affected by the use of fertilizers and the burning of fossil fuels and crops residues. (As an example of the scale of the issue, one locational study suggested that the health-related costs of agriculture are approximately half the value of the agriculture itself [Paulot and Jacob 2014].)
- The concentration of GHGs, which are a major driver of climate change. (AVCs emit as much as 30 percent of anthropogenic GHGs [Bajželj et al. 2013; Poore and Nemecek 2018].)

The per capita environmental footprint of AVCs is significant. Each global citizen's AVC use averaged about three-quarters of a hectare of land (Davis et al. 2016); 776 tons of water, typically mostly rainwater (Davis et al. 2016); 284 g of pesticide-active ingredient (FAOSTAT as of 2015); 9 g of antimicrobials (van Boeckel et al. 2015); and 15 kg of nitrogen fertilizer (Davis et al. 2016), while at the same time emitting just over 2000 kg of CO_2 equivalent (IPCC 2019).

Concerns about deteriorating resilience to growing risks abound. The number of natural disasters worldwide has been increasingly steadily, up more than threefold from 1980 to 2019, with most associated losses uninsured, especially in the low- and middle-income countries (LMICs) where insurance coverage is less than 10 percent (Munich Reinsurance 2020). Massive shocks that disrupt agricultural production more specifically (e.g., droughts, flooding, deadly tropical storms,

[5] We note, however, that soil carbon sequestration capacity diminishes as soils saturate, while tree growth's sequestration potential does not taper as much, if at all. Both are, however, reversible with changes in soil and forest management practices.

locusts, fall armyworm, and other pests) have, likewise, grown in frequency, severity, and potential for co-occurrence with other shocks that compound damages. The COVID-19 pandemic is unlikely to be the last one of this century, so learning lessons from the massive disruptions of 2020 will be imperative to building back better and more resilient in the future. Largely due to war, but increasingly due to climate change, according to the United Nations High Commissioner for Refugees, 80 million forcibly displaced people had fled their homelands at the end of 2019, more than at any time since World War II (UNHCR 2020). Addressing humanitarian needs is far more costly in both human and financial terms the further people move from their homes.

Nonetheless, the scope for AFS changes to reduce hunger and acute malnutrition grow increasingly limited. The reason is that outside of zones of active, violent conflict (e.g., Yemen currently; Somalia, especially in 2011; or South Sudan, Northeast Nigeria, and eastern Democratic Republic of the Congo episodically over the past decade) and states with severe governance problems (e.g., North Korea or Venezuela) famine and near-famine conditions have largely disappeared with advances in early warning systems and humanitarian response, greater interregional market integration, and more inclusive and effective social protection programs (Alderman et al. 2017; Maxwell and Hailey 2020). The acute malnutrition and chronic hunger problems that motivated the last concerted global efforts at AFS transformation in the 1960s and 1970s have become primarily problems of conflict resolution and humanitarian response (Barrett 2021).

The growing link between acute malnutrition and humanitarian response, together with heightened concerns of fragility in key tropical ecosystems, have rapidly drawn attention to broad questions of resilience (Barrett and Constas 2014; Hoddinott 2014; Tendall et al. 2015; Béné 2020). Resilience encompasses notions of resistance to, and recovery from, shocks. Will a shock perturb food supply or access to food? If so, how great a perturbation will occur, and how quickly and closely will it return to—or improve upon—previous functionality?

Resilience, whether at the production level or at the food system level, typically arises through one or both of two mechanisms: functional redundancy and diversity. The first typically would arise from having spare capacity (e.g., food stores for supplies, or decentralized processing so that there is no single point of failure). The second would include diversity in food products, suppliers, geographies, and products (e.g., multiple crop varieties/species or animal breeds/species so that a stress is less likely to hit at the most vulnerable point for all species). Both notions typically run antithetical to standard “efficiency” considerations, which rely on monocultures optimized for typical conditions and just-in-time supply chains that engage preferred suppliers who are highly specialized with no scope for substitution of products.

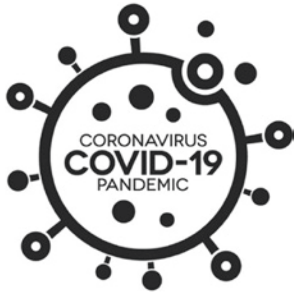
Building resilience, therefore, almost inevitably requires incurring additional costs relative to the way well-resourced AFSs have evolved under intense uninsured cost-minimization pressures from short-run profit-minded companies and investors. Socially optimal pricing must build in the cost of insurance against catastrophic shocks. Companies that embrace the transformational changes required and undertake appropriately ambitious actions recognize this risk and can ensure the appropriate long-term thinking and funding to enable the needed changes. When made part of a company's purpose, this reorientation has proved capable of attracting like-minded investors, as well as having beneficial impacts on other factors such as employee retention and brand loyalty.

> BUILDING RESILIENCE, THEREFORE, ALMOST INEVITABLY REQUIRES INCURRING ADDITIONAL COSTS RELATIVE TO THE WAY WELL-RESOURCED AGRI-FOOD SYSTEMS HAVE EVOLVED UNDER INTENSE UNINSURED COST-MINIMIZATION PRESSURES FROM SHORT-RUN PROFIT-MINDED COMPANIES AND INVESTORS.

From an ecological perspective, AVCs typically reduce ecological resilience by reducing diversity. Agriculture modifies landscapes from small to large scales in multiple ways, typically creating homogeneity at scale (Benton et al. 2003). As a result, across about two-thirds of the Earth's land surface, ecological communities have been radically affected (Newbold et al. 2016). "Modern" agriculture commonly creates input-intensive monocultures by amalgamating small parcels of land into large, uniform blocks, accelerating the decline of both agricultural and wild biodiversity (Kremen and Miles 2012). Actively removing heterogeneity in the environment leaves the world vulnerable to pathogens and pests that can decimate crops at massive scale (Fones et al. 2020), depletes beneficial soil microbial communities (Zhao et al. 2018; Tang et al. 2019), and can allow weed communities to thrive (Poggio 2005) partially due to soil nutrient depletion occurring under uniform cropping patterns (Ehrmann and Ritz 2014).

Modern agriculture increasingly relies on inputs that have direct effects that bost farm productivity (e.g., pesticides killing pests) but which also kill "non-target organisms" (e.g., non-pests which may be the natural enemies of pests) and adversely spill over to other habitats, while also depending on fertilizers that negatively affect air and water quality. Large-scale enterprises can achieve efficiencies of scale and scope that boost conventional economic measures of total factor productivity but concentrate adverse impacts, as when intensive, large-scale livestock enterprises create mass manure lagoons that are difficult to manage and risk catastrophic damage to nearby watersheds. Habitat complexity on a local scale is particularly important for maintaining specialist predator populations that are important for pest control (Chaplin-Kramer et al. 2011).

Lessons from the COVID-19 Pandemic: Directing Inevitable AVC Innovation[6]



The COVID-19 pandemic serves as both a warning and an accelerator. As above, the data support both optimistic and pessimistic interpretations, revealing strengths, vulnerabilities, and weaknesses of modern AFSs. The pandemic has also underscored that simply returning to what was previously "normal" will not be good enough.

Massive disruptions within AVCs have been commonplace throughout history. But most prior disruptions have been driven by supply-side shocks arising from a crop failure, a livestock disease outbreak, etc. In such cases, downstream buyers responded by finding other suppliers or drawing down stored commodities, bidding up prices temporarily until supply recovered. But in the COVID-19 pandemic, supply-side shocks have been largely restricted to some (relatively modest) labor supply disruptions, especially in Europe and India, arising from some nations' restrictions on worker migration or due to disease outbreaks in sites where workers operate in very close proximity to one another (e.g., slaughterhouses in Brazil and the US or at fruit and vegetable packing factories). Overall, primary production has proved remarkably robust. Indeed, the Food and Agriculture Organization (FAO) forecasts record global harvests for 2020.

The world has likewise grown accustomed to isolated logistics disruptions associated with natural disasters (e.g., floods or earthquakes that knock out roads or bridges) or war and other forms of violence that disrupt the flow of food and drive up costs in specific, disaster-affected regions. Despite food export bans—most of them lasting only a few weeks—imposed by at least 20 different national governments (Laborde et al. 2020) and massive shutdown of commercial passenger transport, merchandise freight shipments have been largely untouched, especially in multinational firms' global supply chains. Virtually all AVCs recovered reasonably quickly to supply-side and logistics-driven disruptions associated with COVID-19.

[6] Icon courtesy of Covid Vectors by Vecteezy (https://www.vecteezy.com/free-vector/covid). A revised version of this sub-section appeared as Barrett et al. (2021).

The damage to AVCs from the COVID-19 pandemic, for the first time in living memory, occurred overwhelmingly from a massive demand-side shock to AVCs, as widespread closure of many businesses (disproportionately food service operations—both commercial ones like restaurants or entertainment venues, and institutional ones such as school cafeterias) left hundreds of millions of people worldwide suddenly without jobs and the income to acquire a healthy diet (Barrett 2020). The loss of livelihoods has nearly doubled the number of people worldwide suffering acute food insecurity, to an estimated 270 million.[7] This sparked long lines for private food assistance and sharp expansion of public food assistance.

Meanwhile, **food service accounts for a large and growing share of food consumption globally—roughly half of all consumer food expenditures in high-income countries**—so the pandemic represented a massive disruption to AVCs structured around serving people food away from home. The unprecedentedly fast and severe economic shock induced panic buying as food consumers were forced to redirect virtually all of their demand towards retail outlets. The shuttering of food service enterprises and resulting shutdown of value chains built to deliver to those outlets caught many farmers and food manufacturers with unsellable perishable products. Livestock farmers were effectively compelled to euthanize animals and to dump milk and eggs into waste lagoons. Horticultural producers plowed ripe fruits and vegetables back into their fields. And manufacturers ran out of warehouse storage space for bulk processed goods packaged for institutional buyers.

The most common responses by governments and private charitable organizations have been (1) public health measures to control and treat COVID-19, and (2) unprecedented expansion of safety net and social protection programs (Gentilini et al. 2020). The mechanisms for doing so have varied markedly across, and within, countries—from universal basic income programs, to employment guarantee schemes, government payroll subsidy programs, enhanced unemployment insurance, and expanded access to food assistance. In the short interval of March–September 2020, 212 different countries/territories announced and/or implemented an astounding 1,179 different social protection measures in response to the massive dislocations caused by the COVID-19 pandemic (Gentilini et al. 2020). The necessity of supporting consumer demand, especially

[7] Per the UN World Food Programme estimates from June 2020 (https://www.wfp.org/news/world-food-programme-assist-largest-number-hungry-people-ever-coronavirus-devastates-poor).

among the poorest and most vulnerable, has been the centerpiece of societal response, not only to the pandemic in general but also to cushioning AFSs from the demand shock.

Overall, AVC intermediaries adapted quickly, switching among value chains and service modes. Restaurants quickly flipped to delivery, takeout, and outdoor dining options. Processors modified manufacturing processes to expand retail-oriented packaging while reducing wholesale packaging for food service clients.

Some of these adaptations are likely to prove permanent, as the pandemic boosted consumers' and companies' awareness of the value chains on which they draw, and farmers have become more aware of what happens downstream after they sell their product. This awareness has accelerated change towards online grocery purchases and food delivery, community-supported agriculture and similar direct-to-consumer arrangements, and home gardens. Ventures such as Malaysia's Myfishman.com, which connects fishermen to individual consumers, have flourished worldwide while communities have revived gleaning as a way to reduce food loss and improve poor consumers' access to healthy fresh foods.[8]

Already-growing demand for plant-based meat substitutes has likewise increased as consumers grew more concerned about the sustainability of production systems and the potential for food contamination in long value chains (Siegrist and Hartmann 2019; Van Loo et al. 2020; Jalil et al. 2020).[9] Crop and dairy farms, meatpackers, and other AVC firms have sharply stepped up investment in robots invulnerable to infectious disease transmission. Farmers, traders, manufacturers, and food service vendors have rapidly expanded their use of e-commerce platforms to help find customers and suppliers. Farmers and processors have adopted creative approaches to improve worker safety and firm resil-

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[8] Gleaning is a centuries-old tradition of mobilizing small groups to collect edible crop left in the field after a harvest, or of unsellable crops left in the field. In the US, for example, 6–7 percent of planted acreage is unharvested because of cosmetic blemishes, mechanical harvesting error, or a lack of market for the crop (https://www.nytimes.com/2020/07/06/dining/gleaners-farm-food-waste.html; https://www.sciencedirect.com/science/article/pii/S0306919216301026).

[9] For example, Impossible Foods expanded its retail distribution of plant-based beef substitutes from less than 200 stores in January 2020 to more than 3000 stores by May 2020 (Nierenberg, *Wall Street Journal*, May 22, 2020), while Beyond Meat's revenue increased 69 percent year-on-year to June 2020 (Maidenberg, *Wall Street Journal*, August 4, 2020). See also Shahbandeh (2020, https://www.statista.com/topics/6057/meat-substitutes-market-in-the-us/). The global plant-based meat market is predicted to exceed US$35 billion by 2027 (Polaris 2020).

ience, such as the Nigerian chicken processors who organized dedicated bus transport for workers on more sparsely staffed shifts at factories (Reardon and Swinnen 2020). Meanwhile, governments and charitable organizations have doubled down on the use of mobile digital transfers of cash and vouchers for food assistance. Many of these changes are welcome advances unlikely to reverse once the health scare and economic dislocation of the pandemic passes.

The pandemic has also laid bare great structural inequities of risk exposure within AFSs. In high-income countries, "essential" workers in grocery stores, food delivery services, densely-packed meatpacking plants, etc., suffered far higher rates of infection and death than the food consumers they serve or white-collar executives in those same sectors. Essential workers were more likely to be people of color, not to have graduated from university, and to have lower income—all strong correlates of obesity and diet-related non-communicable diseases such as diabetes and hypertension. Those structural inequities existed long before the pandemic but have been magnified by it. More than a century after Upton Sinclair's *The Jungle* called attention to the inhumane working conditions in meatpacking plants, a groundswell of concern has reemerged about protecting farmworkers and meatpackers, both for their benefit and so as to safeguard food supplies and stem disease transmission from workers who migrate to follow harvest periods.

The COVID-19 pandemic has made clear that **healthfulness, equity, resilience, and sustainability are interlinked, precompetitive issues. They concern our collective fitness as a species when faced with covariate shocks** like pandemics, climate change, and mass extinctions. And this is a centerpiece of the challenge before us. Incentives that skew excessively towards the promotion of individual interests can undermine collective action (Ostrom 2010). Then virtually everyone is worse off because, as elementary game theory makes clear, cooperative outcomes are almost always superior to noncooperative ones, but cooperation typically arises only when the rules of the game naturally induce a critical mass of people to do so.

Trust underpins cooperation (Barrett 1997; Ostrom 2010). The pandemic has made clear the importance of cultural and political responses to scientific uncertainty and trust in expert guidance. Responses have varied wildly across, and within, countries. If cooperation is the watchword on precompetitive issues, then many communities have failed this recent, lethal test, as basic public health measures became deeply politicized. The pandemic is a trial run not just for inevitable, future infectious disease outbreaks, but also for climate change and biodiversity loss. These are, likewise, natural processes but with even larger-scale and longer-lasting implications for humanity and the AFSs that support us than that of COVID-19. As societies impose major sacrifices on younger generations in order to protect more vulnerable older populations, will reciprocity emerge wherein the older adults, who exercise most power in economic and political systems, accept responsibility to make some near-term sacrifices as investments to protect today's young and as-yet-unborn generations from avoidable ravages of climate change?

THE COVID-19 PANDEMIC HAS MADE CLEAR THAT HEALTHFULNESS, EQUITY, RESILIENCE, AND SUSTAINABILITY ARE INTERLINKED, PRECOMPETITIVE ISSUES. THEY CONCERN OUR COLLECTIVE FITNESS AS A SPECIES WHEN FACED WITH COVARIATE SHOCKS LIKE PANDEMICS, CLIMATE CHANGE, AND MASS EXTINCTIONS.

Even as science has become further politicized in some places during the pandemic, we have witnessed historically unprecedented mobilization of finance for basic and applied science to seek vaccines to prevent, and treatments for, COVID-19. Creative arrangements have emerged—not just conventional research contracts and grants to research institutions, or venture capital, conventional debt or equity financing of private laboratories, but also advanced market commitments to ensure a large-scale, remunerative commercial market necessary to induce private investment while simultaneously ensuring widespread access in low-income countries (GAVI 2020; Kremer et al. 2020).

The intellectual property behind whatever successful discoveries emerge will inevitably be hotly contested within, and among, countries. Pre-existing patents have not, however, impeded R&D progress, which has advanced at an unprecedented pace. Before COVID, the fastest vaccine ever developed, against mumps, took four years from initial sample collection and identification until vaccines were licensed for approved distribution. As this report goes to press, we appear on the cusp of vaccine approvals in just months, well under a year since the virus was first identified! The astounding pace of progress seems partly due to the Open-COVID Pledge launched in April 2020, which enables biomedical researchers to freely share their IP following a model similar to that used for open-source software; the pledge covered more than 250,000 patents worldwide by end-July (Contreras et al. 2020). **The COVID-19 experience clearly demonstrates that massive amounts of financing, scientific talent, and popular support can be mobilized quickly with adequate political will and a shared sense of urgency**, which are equally needed for the task of AFS transformation.

Mainly, the pandemic has been a wake-up call to prepare and build back better. The unprecedented global scale and speed of this shock to AFSs compel change. Return to the *status quo ex ante* seems both unlikely and unwise. At a defining moment when paths will almost-inevitably shift, we must focus intently on crafting innovation pathways that can effectively navigate the world from its current vulnerable condition to our desired states. The pandemic creates an opportunity to address systemic needs arising from other pressures (e.g., climate change) but to which the world has, to date, been insufficiently responsive. This can be a moment of "creative destruction," to invoke Joseph Schumpeter's famous term (Schumpeter 1942), a moment for dismantling established processes that cannot possibly deliver healthy diets, equitable and inclusive livelihoods, environmental sustainability, and resilience to shocks and stressors, and to replace them in a dynamic process of innovation and adaptive management. The following **thirteen key**, general lessons for AFSs stand out from the COVID-19 pandemic experience:

Stuff happens… be ready. This isn't a one-off, short-run shock. No sensible person believes this pandemic will be the last major challenge of our lifetimes. We must be prepared for more severe and more frequent, compound shocks, as well as for simultaneous and cascading shocks. This implies we need greater redundancy and resilience in AFSs and AVCs.

Expect that ever-ready social safety nets are needed. The pandemic's pain has aggravated underlying inequalities. Nations and communities need reliable, scalable social protection programs that are sensitive to race, gender, ethnicity, and other dimensions of systemic discrimination. These cannot be built on the fly. Weak or incomplete social protection mechanisms undermine solidarity and cooperation within society, thereby discouraging responsible individual behaviors and hurting everyone.

Beware slower-moving catastrophes. The pandemic was fast-moving, compelling policymaker attention. We must beware slower-moving—but no less consequential—shocks, such as those due to climate change, biodiversity and habitat loss, sea level rise, etc. Slower transition can engender complacency—the mythical frog-in-the-water-as-it-warms problem—and can imply lesser ability to get the shock under control once people finally feel compelled to act.

Realize that massive resources can be mobilized quickly. Trillions of dollars have been appropriated by governments in just a few months. Where the needs are apparent and political leaders feel compelled to act, funds can be found fast (Herrero and Thornton 2020).

Move beyond uninsured cost minimization. Affordable, healthy diets are crucial for equity purposes but often involve resilience and sustainability tradeoffs. **De-risking AFSs requires greater diversification of production, sourcing, processing, and distribution patterns to enhance flexibility and redundancy**. This has a cost but also a value, as costly insurance against catastrophic systemic risk always does.

Beware de-globalization. Supply chain disruptions have fueled many governments to pursue food self-sufficiency more aggressively. This carries significant prospective risk. First, **de-globalization can harm the poor by making healthy diets more expensive**. Second, it can undermine environmental and climate sustainability because *how* a product is produced, processed, and distributed matters far more to its footprint than *where* it was made (Poore and Nemecek 2018). Third, trade is essential to manage changing climate (Baldos and Hertel 2015). Fourth, the more countries disengage from one another and pursue trade wars, the greater the likelihood of interstate conflict, which is the single greatest cause of severe acute malnutrition globally (Barrett 2013). Build more diversified and resilient AVCs, but be careful about hidden nationalist agendas.

Fund and trust first-rate science. Technical skill is essential preparation. We can adaptively manage and innovate only if we can learn fast. **We cannot build scientific and engineering capacity overnight but can undermine it quickly through poor communications, especially if leaders let politics overrule, and even misrepresent science**.

Understand that barriers to success are more behavioral than scientific. Although the science on COVID-19 has progressed at unprecedented speed, behavioral adjustments have proved far slower and more uneven across communities. Culture change is key and requires convincing social influencers and thought leaders to do things differently as we learn. This also requires checks and balances to avoid excessive concentration of political/commercial power, which has strong conservative tendencies to entrench itself.

Recognize that clear, consistent, trusted incentives and norms are key. No coordinated response emerged at global scale and not even at national scale in most countries. **The enormous numbers of independent agents throughout centralized AVCs made market incentives and social norms, not top-down directives other than to drive incentives and calibrate norms, the key policy instruments**. Decentralized, market-based AVCs self-stabilized reasonably quickly and well under the circumstances, especially where markets were allowed to induce rapid response to shutdowns in AVC subsectors.

Value communication, transparency, and cooperation as essential. Spillovers are ever-present, so strong coordinating institutions are essential to build and maintain trust so as to quickly identify and contain contagion. Because trust inevitably requires verification, traceability is increasingly at a premium.

Assume that dramatic, fast improvements are possible. Behavioral change is hard but feasible. Societies worldwide rapidly adjusted, virtually shutting sectors (e.g., food service, commercial transport). This generated sharp reduction in disease transmission and in GHG and pollution emissions. These results demonstrate clearly that we can dramatically improve outcomes if we have the incentives to exert ourselves.

Treat underlying causes, not just symptoms. Pandemics are the long-predicted consequence of habitat and biodiversity loss (partly due to expanding land use in agriculture) that increases exposure to zoonoses, of inconsistent and non-transparent food safety regulations, and of insufficient integration between food and health systems. Root cause analysis is key to ensure each limiting factor is identified.

Emphasize high-frequency monitoring. Systemic shocks require near-real-time monitoring of fast-changing conditions. Innovations in remote sensing, digital records, "sewage epidemiology" (monitoring biomarkers for disease and other exposures in human and animal waste streams), and crowd-sourcing open up new opportunities to improve the timeliness and cost-effectiveness of responses to systemic shocks.

Crises inevitably spark innovation. The crucial questions are what sorts of innovation will happen as AVCs recover from the COVID-19 pandemic, and how can we best induce beneficial innovations? Because a disproportionate share of the reconstruction of AVCs will—and must—happen in the coming 2–5 years, near-term innovations—in institutions and policies, as much as in technologies—will likely lock in for some time as investors and policymakers amortize the sunk costs they incur. So we need to influence today's innovations with an eye to decades hence. What should the design objectives be, and what will AFSs and AVCs look like in 25–50 years (i.e., the lifespan of a current person of median global age)?

References

Adiele, J.G., A.G.T. Schut, R.P.M. van den Beuken, K.S. Ezui, P. Pypers, A.O. Ano, C.N. Egesi, and K.E. Giller. 2020. Towards closing cassava yield gap in West Africa: Agronomic efficiency and storage root yield responses to NPK fertilizers. *Field Crops Research* 253: 107820.

Alderman, Harold, Ugo Gentilini, and Ruslan Yemtsov. 2017. *The 1.5 billion people question: Food, vouchers, or cash transfers?* Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1087-9.

Alston, Julian M., Jason M. Beddow, and Philip G. Pardey. 2009. Agricultural research, productivity, and food prices in the long run. *Science* 325 (5945): 1209–1210. https://doi.org/10.1126/science.1170451.

Amundson, Ronald, Asmeret Asefaw Berhe, Jan W. Hopmans, A. Carolyn Olson, Ester Sztein, and Donald L. Sparks. 2015. Soil science: Soil and human security in the 21st century. *Science* 348 (6235): 1261071. https://doi.org/10.1126/science.1261071.

Bajželj, Bojana, Julian M. Allwood, and Jonathan M. Cullen. 2013. Designing climate change mitigation plans that add up. *Environmental Science & Technology* 47 (14): 8062–8069. https://doi.org/10.1021/es400399h.

Baldos, Uris, and Thomas Hertel. 2015. The role of international trade in managing food security risks from climate change. *Food Security* 7 (April). https://doi.org/10.1007/s12571-015-0435-z.

Barrett, Christopher B. 1997. Idea gaps, object gaps, and trust gaps in economic development. *Journal of Developing Areas* 31 (4): 553.

Barrett, Christopher B. (ed.). 2013. *Food security and sociopolitical stability*. Oxford: Oxford University Press.

Barrett, Christopher B. 2020. Actions now can curb food systems fallout from COVID-19. *Nature Food* 1 (6): 1–2. https://doi.org/10.1038/s43016-020-0085-.

Barrett, Christopher B. 2021. Overcoming global food security challenges through science and solidarity. *American Journal of Agricultural Economics* 103 (2): 422–447.

Barrett, Christopher B., Luc Christiaensen, Megan Sheahan, and Abebe Shimeles. 2017. On the structural transformation of rural Africa. Policy Research Working Papers. The World Bank. https://doi.org/10.1596/1813-9450-7938.

Barrett, Christopher B., and Mark A. Constas. 2014. Toward a theory of resilience for international development applications. *Proceedings of the National Academy of Sciences of the United States of America* 111 (40): 14625. https://doi.org/10.1073/pnas.1320880111.

Barrett, Christopher B., Jessica Fanzo, Mario Herrero, Daniel Mason-D'Croz, Alexander Mathys, Philip Thornton, Stephen Wood, Tim G. Benton, Shenggen Fan, Laté Lawson-Lartego, Rebecca Nelson, Jianbo Shen, and Lindiwe Majele Sibanda. 2021. COVID-19 pandemic lessons for agri-food systems innovation. *Environmental Research Letters* 16 (10): 101001. https://doi.org/10.1088/1748-9326/ac25b9.

Béné, Christophe. 2020. Resilience of local food systems and links to food security—A review of some important concepts in the context of COVID-19 and other shocks. *Food Security* 12 (4): 805–822. https://doi.org/10.1007/s12571-020-01076-1.

Benton, Tim G., Juliet A. Vickery, and Jeremy D. Wilson. 2003. Farmland biodiversity: Is habitat heterogeneity the key? *Trends in Ecology & Evolution* 18 (4): 182–188. https://doi.org/10.1016/S0169-5347(03)00011-9.

Bloom, Nicholas, Charles I. Jones, John Van Reenen, and Michael Webb. 2020. Are ideas getting harder to find? *American Economic Review* 110 (4): 1104–1144. https://doi.org/10.1257/aer.20180338.

Cattaneo, Andrea, Marco V. Sánchez, Máximo Torero, and Rob Vos. 2020. Reducing food loss and waste: Five challenges for policy and research. *Food Policy*, September, 101974. https://doi.org/10.1016/j.foodpol.2020.101974.

Chai, Yuan, Philip G. Pardey, Connie Chan-Kang, Jikun Huang, Kyuseon Lee, and Wanlu Dong. 2019. Passing the food and agricultural R&D buck? The United States and China. *Food Policy* 86 (July): 101729. https://doi.org/10.1016/j.foodpol.2019.101729.

Chaplin-Kramer, Rebecca, Megan E. O'Rourke, Eleanor J. Blitzer, and Claire Kremen. 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecology Letters* 14 (9): 922–932. https://doi.org/10.1111/j.1461-0248.2011.01642.x.

Contreras, Jorge L., Michael Eisen, Ariel Ganz, Mark Lemley, Jenny Molloy, Diane M. Peters, and Frank Tietze. 2020. Pledging intellectual property for COVID-19. *Nature Biotechnology* 38 (10): 1146–1149. https://doi.org/10.1038/s41587-020-0682-1.

Cooper, Karen A., Tom E. Quested, Helene Lanctuit, Diane Zimmermann, Namy Espinoza-Orias, and Anne Roulin. 2018. Nutrition in the bin: A nutritional and environmental assessment of food wasted in the UK. *Frontiers in Nutrition* 5 (March). https://doi.org/10.3389/fnut.2018.00019.

Dalin, Carole, Yoshihide Wada, Thomas Kastner, and Michael J. Puma. 2017. Groundwater depletion embedded in international food trade. *Nature* 543 (7647): 700–704. https://doi.org/10.1038/nature21403.

Davis, Kyle F., Jessica A. Gephart, Kyle A. Emery, Allison M. Leach, James N. Galloway, and Paolo D'Odorico. 2016. Meeting future food demand with current agricultural resources. *Global Environmental Change* 39 (July): 125–132. https://doi.org/10.1016/j.gloenvcha.2016.05.004.

Dolislager, Michael, Thomas Reardon, Aslihan Arslan, Louise Fox, Saweda Liverpool-Tasie, Christine Sauer, and David L. Tschirley. 2021. Youth and adult agrifood system employment in developing regions: Rural (peri-urban to hinterland) vs. Urban. *The Journal of Development Studies* 57 (4): 571–593. https://doi.org/10.1080/00220388.2020.1808198.

Ehrmann, Jürgen, and Karl Ritz. 2014. Plant: Soil interactions in temperate multi-cropping production systems. *Plant and Soil* 376 (1): 1–29. https://doi.org/10.1007/s11104-013-1921-8.

Evenson, Robert E., and Douglas Gollin. 2003. Assessing the impact of the Green Revolution, 1960 to 2000. *Science* 300 (5620): 758–762. https://doi.org/10.1126/science.1078710.

Fanzo, Jessica, Lawrence Haddad, Rebecca McLaren, Quinn Marshall, Claire Davis, Anna Herforth, Andrew Jones, et al. 2020. The food systems dashboard is a new tool to inform better food policy. *Nature Food* 1 (5): 243–246. https://doi.org/10.1038/s43016-020-0077-y.

FAO. 2019. *The state of food and agriculture 2019: Moving forward on food loss and waste reduction.* Rome.

Fogel, Robert William. 2004. *The escape from hunger and premature death, 1700–2100: Europe, America, and the Third World.* Cambridge Studies in Population, Economy and Society in Past Time. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511817649.

Fones, Helen N., Daniel P. Bebber, Thomas M. Chaloner, William T. Kay, Gero Steinberg, and Sarah J. Gurr. 2020. Threats to global food security from emerging fungal and oomycete crop pathogens. *Nature Food* 1 (6): 332–342. https://doi.org/10.1038/s43016-020-0075-0.

Fuglie, Keith, Madhur Gautam, Aparajita Goyal, and William F. Maloney. 2020. *Harvesting prosperity: Technology and productivity growth in agriculture*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1393-1.

GAVI. 2020. Gavi launches innovative financing mechanism for access to COVID-19 vaccines. June 4, 2020. https://www.gavi.org/news/media-room/gavi-launchesinnovative-financing-mechanism-access-covid-19-vaccines.

GBD 2017 Diet Collaborators. 2019. Health effects of dietary risks in 195 countries, 1990–2017: A systematic analysis for the global burden of disease study 2017. *Lancet* 393 (10184): 1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8.

Gentilini, Ugo, Mohamed Almenfi, Pamela Dale, Robert Palacios, Harish Natarajan, Guillermo Alfonso Galicia Rabadan, Yuko Okamura, John Blomquist, Miglena Abels, Gustavo Demarco, and Indhira Santos. 2020. *Social protection and jobs responses to COVID-19: A real-time review of country measures*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/33635.

Gollin, Douglas, Casper Worm Hansen, and Asger Wingender. 2018. *Two blades of grass: The impact of the Green Revolution*. No. w24744. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w24744.

Haddad, Lawrence. 2020. Viewpoint: A view on the key research issues that the CGIAR should lead on 2020–2030. *Food Policy* 91 (February): 101824. https://doi.org/10.1016/j.foodpol.2020.101824.

Herrero, Mario, and Philip Thornton. 2020. What can COVID-19 teach us about responding to climate change? *The Lancet. Planetary Health* 4 (5): e174. https://doi.org/10.1016/S2542-5196(20)30085-1.

Hoddinott, John F. 2014. *Resilience: A primer*. 2020 Conference Brief 8. May 17–19, Addis Ababa, Ethiopia. International Food Policy Research Institute (IFPRI): Washington, DC. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/128159.

International Labour Organization (ILO). 2015. Agriculture: A hazardous work. Geneva: ILO. Accessed November 7, 2020. https://www.ilo.org/global/topics/safety-and-health-at-work/areasofwork/hazardous-work/WCMS_356550/lang--en/index.htm.

International Labour Organization (ILO). 2017. Working together to promote a safe and healthy working environment. Report of the International Labour Conference 2017. Geneva: ILO.

IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages. https://doi.org/10.5281/zenodo.3553579.

IPCC. 2019. Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, eds. https://www.ipcc.ch/srccl/.

Jalil, Andrew, Joshua Tasoff, and Arturo Bustamante. 2020. Eating to save the planet: Evidence from a randomized controlled trial using individual-level food purchase data. *Food Policy* 95 (August): 101950. https://doi.org/10.1016/j.foodpol.2020.101950.

Kanter, David R., Olivia Chodos, Olivia Nordland, Mallory Rutigliano, and Wilfried Winiwarter. 2020. Gaps and opportunities in nitrogen pollution policies around the world. *Nature Sustainability* 3: 956–963. https://doi.org/10.1038/s41893-020-0577-7.

Kremen, Claire, and Albie Miles. 2012. Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. *Ecology and Society* 17 (4). https://www.jstor.org/stable/26269237.

Kremer, Michael, Jonathan Levin, and Christopher M. Snyder. 2020. Advance market commitments: Insights from theory and experience. *AEA Papers and Proceedings* 110 (May): 269–273. https://doi.org/10.1257/pandp.20201017.

Laborde, David, Marie Parent, and Carin Smaller. 2020. *Ending hunger, increasing incomes, and protecting the climate: What would it cost donors?* Washington: Ceres2030, International Institute for Sustainable Development, and International Food Policy Research Institute.

Mason-D'Croz, Daniel, Timothy B. Sulser, Keith Wiebe, Mark W. Rosegrant, Sarah K. Lowder, Alejandro Nin-Pratt, Dirk Willenbockel, et al. 2019. Agricultural investments and hunger in Africa modeling potential contributions to SDG 2—Zero hunger. *World Development* 116 (April): 38–53. https://doi.org/10.1016/j.worlddev.2018.12.006.

Maxwell, Daniel, and Peter Hailey. 2020. Towards anticipatory information systems and action: Notes on early warning and early action in East Africa. Boston: Feinstein International Center, Tufts University; Nairobi: Centre for Humanitarian Change.

Mellor, John W. 2017. *Agricultural development and economic transformation: Promoting growth with poverty reduction*. New York, NY: Palgrave Macmillan.

Munich Reinsurance. 2020. Risks posed by natural disasters. Accessed November 1, 2020. https://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards.html#-1624621007.

Newbold, Tim, Lawrence N. Hudson, Andrew P. Arnell, Sara Contu, Adriana De Palma, Simon Ferrier, Samantha L. L. Hill, et al. 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* 353 (6296): 288–291. https://doi.org/10.1126/science.aaf2201.

Ortiz-Bobea, Ariel, Toby R. Ault, Carlos M. Carrillo, Robert G. Chambers, and David B. Lobell. 2020. The historical impact of anthropogenic climate change on global agricultural productivity. ArXiv E-Prints 2007 (July): arXiv:2007.10415.

Ostrom, Elinor. 2010. Beyond markets and states: Polycentric governance of complex economic systems. *The American Economic Review* 100 (3): 641–672.

Pardey, Philip G., Connie Chan-Kang, Steven P. Dehmer, and Jason M. Beddow. 2016. Agricultural R&D is on the move. *Nature News* 537 (7620): 301. https://doi.org/10.1038/537301a.

Paulot, Fabien, and Daniel J. Jacob. 2014. Hidden cost of U.S. agricultural exports: Particulate matter from ammonia emissions. *Environmental Science & Technology* 48 (2): 903–908. https://doi.org/10.1021/es4034793.

Pelletier, Johanne, Hambulo Ngoma, Nicole M. Mason, and Christopher B. Barrett. 2020. Does smallholder maize intensification reduce deforestation? Evidence from Zambia. *Global Environmental Change* 63 (July): 102127. https://doi.org/10.1016/j.gloenvcha.2020.102127.

Pingali, Prabhu L. 2012. Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences* 109 (31): 12302–12308. https://doi.org/10.1073/pnas.0912953109.

Poggio, Santiago L. 2005. Structure of weed communities occurring in monoculture and intercropping of field pea and barley. *Agriculture, Ecosystems & Environment* 109 (1): 48–58. https://doi.org/10.1016/j.agee.2005.02.019.

Polaris Market Research. 2020. *Plant-based meat market share, size, trends, industry analysis report, by source (soy, wheat, pea, and others); By product (burger patties, sausages, strips & nuggets, meatballs, others); By application (retail outlets, foodservice, E-commerce), by regions; Segment forecast, 2020 –2027*. Report PM1689. New York: Polaris Market Research.

Poore, J., and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360 (6392): 987–992. https://doi.org/10.1126/science.aaq0216.

Reardon, Thomas, and Johan Swinnen. 2020. COVID-19 and resilience innovations in food supply chains. In *IFPRI Book Chapters*, 132–136. International Food Policy Research Institute (IFPRI). https://ideas.repec.org/h/fpr/ifpric/133836.html.

Ritchie, Hannah, David S. Reay, and Peter Higgins. 2018. Beyond calories: A holistic assessment of the global food system. *Frontiers in Sustainable Food Systems* 2. https://doi.org/10.3389/fsufs.2018.00057.

Sanchez, Pedro A. 2020. Time to increase production of nutrient-rich foods. *Food Policy* 91 (February): 101843. https://doi.org/10.1016/j.foodpol.2020.101843.

Schumpeter, Joseph A. 1942. *Capitalism, socialism, and democracy*. New York: Harper and Brothers.

Siegrist, Michael, and Christina Hartmann. 2019. Impact of sustainability perception on consumption of organic meat and meat substitutes. *Appetite* 132 (January): 196–202. https://doi.org/10.1016/j.appet.2018.09.016.

Tang, Xiumei, Saiyun Luo, Zhipeng Huang, Haining Wu, Jin Wang, Guoying Shi, Liangqiong He, et al. 2019. Changes in the physicochemical properties and microbial communities of rhizospheric soil after cassava/peanut intercropping. *BioRxiv*, March, 570937. https://doi.org/10.1101/570937.

Tendall, Danielle M., Jonas Joerin, Birgit Kopainsky, Peter J. Edwards, Aimee Shreck, Quang Bao Le, P. Kruetli, Michelle Grant, and Johan Six. 2015. Food system resilience: Defining the concept. *Global Food Security* 6 (October): 17–23. https://doi.org/10.1016/j.gfs.2015.08.001.

Thurlow, James. 2020. Measuring Agricultural Transformation. Presentation to USAID, Washington, DC. Available at: https://www.slideshare.net/ifpri/aggdp-agemp-measuring-agricultural-transformation.

Tilman, David, Kenneth G. Cassman, Pamela A. Matson, Rosamond Naylor, and Stephen Polasky. 2002. Agricultural sustainability and intensive production practices. *Nature* 418 (6898): 671–677. https://doi.org/10.1038/nature01014.

Tilman, David, and Michael Clark. 2014. Global diets link environmental sustainability and human health. *Nature* 515 (7528): 518–522. https://doi.org/10.1038/nature13959.

United Nations High Commissioner for Refugees. 2020. *Figures at a Glance*. UNHCR. June 18, 2020. https://www.unhcr.org/figures-at-a-glance.html.

van Boeckel, Thomas P., Charles Brower, Marius Gilbert, Bryan T. Grenfell, Simon Asher Levin, Timothy P. Robinson, Aude Teillant, and Ramanan Laxminarayan. 2015. Global trends in antimicrobial use in food animals. *Proceedings of the National Academy of Sciences of the United States of America* 112 (18): 5649–5654. https://doi.org/10.1073/pnas.1503141112.

Van Loo, Ellen J., Vincenzina Caputo, and Jayson L. Lusk. 2020. Consumer preferences for farm-raised meat, lab-grown meat, and plant-based meat alternatives: Does information or brand matter? *Food Policy* 95 (August): 101931. https://doi.org/10.1016/j.foodpol.2020.101931.

Yi, Jing, Eva-Marie Meemken, Veronica Mazariegos-Anastassiou, Jiali Liu, Ejin Kim, Miguel I. Gómez, Patrick Canning, and Christopher B. Barrett. 2021. Post-farmgate food value chains make up most of consumer food expenditures globally. *Nature Food* 2 (6): 417–425. https://doi.org/10.1038/s43016-021-00279-9.

Zhao, Qingyun, Wu Xiong, Yizhang Xing, Yan Sun, Xingjun Lin, and Yunping Dong. 2018. Long-term coffee monoculture alters soil chemical properties and microbial communities. *Scientific Reports* 8 (1): 6116. https://doi.org/10.1038/s41598-018-24537-2.