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Overcoming Global Food Security Challenges Through Science and Solidarity

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Food security is both intrinsically and instrumentally important to human flourishing. The consensus definition, agreed at the 1996 World Food Summit, remains that food security exists if and only if "*all people at all times have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*". Food security's intrinsic importance is underscored by the legal right to food recognized in treaties, including Article 25 of the 1948 Universal Declaration of Human Rights and Article 11.2 of the 1966 International Covenant on Economic, Social, and Cultural Rights, and in the constitutions of dozens of countries (Vidar, Kim and Cruz 2014). Even in countries that do not formally recognize a right to food, food security's instrumental importance to economic growth, environmental protection, poverty reduction, public health, and even sociopolitical stability motivates local, national, and international food assistance programs that cover billions of people (Barrett 2013; Alderman, Gentilini and Yemtsov 2017; Gundersen 2019).

Many scholars, policymakers, and media outlets worry quite publicly that global food security may become more tenuous in coming decades. Their quite reasonable anxieties follow naturally from several indisputable observations. First, food demand is poised to grow sharply this century, for multiple reasons. Human population growth is baked into our current demographic structure, given a median age below 30 years in more than 110 countries that collectively represent well more than half the global population (UNDESA 2019). Income growth that is both desirable and inevitable, especially in today's low- and middle-income countries (LMICs), will fuel increased demand for food. That will be especially true for animal sourced foods (ASFs) and processed foods that require greater agricultural feedstock inputs than

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do the starchy staples that comprise the bulk of the diets of the poor. The globe has or will soon reach peak rural population globally. As urbanization continues, to the point that two-thirds to three-quarters of humanity lives in cities (UNDESA 2018), elongated agri-food[2] value chains (AVCs) will likewise require greater agricultural feedstock inputs per capita.

Meanwhile, supply growth through agricultural expansion grows increasingly constrained by urbanization, land degradation, the need to protect ecologically valuable forests, grasslands and wetlands, and water scarcity. We can obviate resource constraints through technological change. But the rate of growth of total factor productivity (TFP) in agriculture has been slowing worldwide (Fuglie et al. 2019), with climate change accounting for a significant share of that decline (Ortiz-Bobea et al. 2020). Further, although AVCs have largely withstood the massive, rapid dislocation of the COVID-19 pandemic, the sheer breadth of lockdowns, outbreaks, and travel restrictions has laid bare many logistical vulnerabilities in AVCs that have been optimized for cost minimization more than for resilience. In the face of inexorably rising food demand over the rest of this century, slowing supply growth and heightened prospects of disruptions, is it any wonder that many well-informed observers fret about the global food security in the future?

The most fundamental point I want to make is that although these challenges are indeed formidable, they are manageable. The world has previously faced and overcome similarly daunting food security challenges by marshaling both scientific advances and social protection innovations. The prospects for similar successes in the coming decades are reasonably good, provided that (i) we learn key lessons from past episodes that likewise sparked widespread worry, (ii) we apply those lessons to tackle tomorrow's challenges, not yesterday's or today's, and (iii) we recognize that faith and investment in science, and solidarity with the poor are each necessary-but-not-sufficient conditions for success. And that is the second fundamental point of this essay, that success in this existential task will require "socio-technical bundles" that combine novel science and engineering with "softer" institutional, policy and sociocultural innovations that unlock the potential of the former, "harder" discoveries.

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[2] As explained in Barrett et al. (2020), I favor "agri-food" over either "agricultural" or "food" to modify "systems" or "value chains." The reason is that many agricultural producers cultivate both food and non-food (e.g., cotton, sisal, tobacco) products, and people consume little food that has not been packaged, prepared, processed or transported off-farm, thereby transforming agricultural feedstocks into human foods. So both the "agricultural" and "food" modifiers are too narrow on their own.

Lessons From Past Successes

Humankind has devised agri-food systems innovations to overcome existential threats since before recorded history. One could go far back in history, to at least 12 millenia ago when various calamities drove semi-nomadic human communities to settle and begin domesticating wild animals and plants into livestock breeds and crop species. We can derive key lessons from just the last century, however.

The Great Depression that began in 1929 across most of the world was soon compounded by the Dust Bowl that wreaked havoc on the vast agricultural region of the American Midwest and Canadian prairies. The resulting spike in food insecurity was rapid and severe, domestically and globally. The United States (US) – and other national and local – governments responded with unprecedented investments in agricultural research and extension, soil and water conservation, and commodity market interventions, all aimed at raising and stabilizing staple crop yields and farmer incomes.[3] The Agricultural Adjustment Act of 1933 begat subsequent US Farm Bills.[4] And the mass human suffering of this period launched a range of New Deal programs that established the modern social protection systems we know today, especially the major food assistance programs.

A period of unprecedented agri-prosperity followed in the rural US and other high-income countries (HICs). Average corn (maize) yields, which averaged 1.5 tons/hectare from 1930-1936 – as they had steadily since the Civil War, 70 years earlier – began near-linear trend growth to more than 10 tons/hectare by the 2010s (Ritchie and Roser 2019). This unprecedented productivity growth was sparked in large part by agricultural research and development (R&D) investments. Improved hybrid seed discoveries financed by public R&D funding rapidly began replacing open-pollinated varieties. These were complemented by advances in both farm machinery that freed up increasingly valuable labor for non-farm work and inorganic nitrogenous fertilizers enabled by the Haber-Bosch process[5] that was a direct response to European fears of a

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[3] Mercier and Halbrook (2020) detail the policy responses and their impacts, both short- and longer-term.

[4] Of course, the landmark 1936 Supreme Court decision in *United States v. Butler* found key provisions of the 1933 Act unconstitutional, which heavily influenced the Farm Bills that followed.

[5] The Haber-Bosch process enables industrial conversion of atmospheric nitrogen (N_2) into ammonia (NH_3) using high temperature and pressure reaction with hydrogen (H_2). Prior to the German chemists' Nobel Prize-winning discovery just prior to World War I, production of nitrogen fertilizer was expensive and difficult to scale.

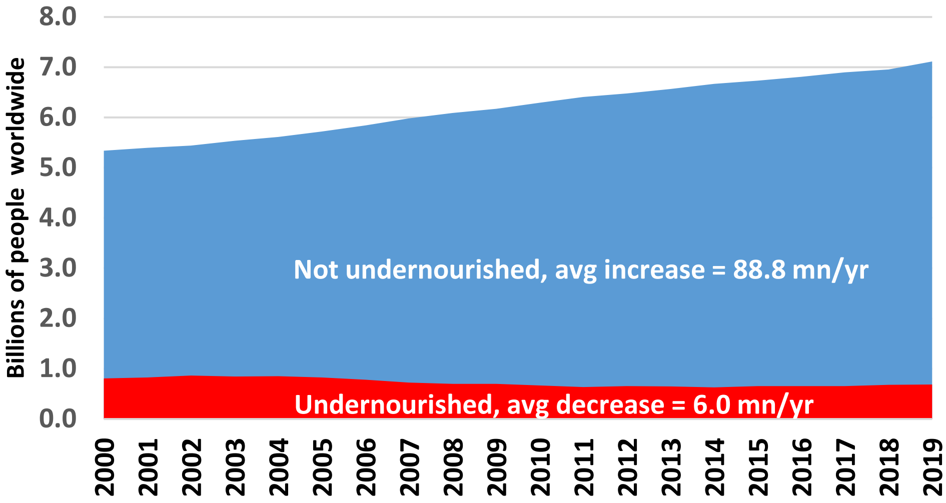
looming food crisis post-World War I. The result was a boom in US agricultural output, and steadily falling real food prices.

But technological change, like price policy, inevitably generates both losers and winners. The same factors that increase the propensity for some people to start off poor – bad luck, lesser endowments, sociopolitical marginalization – also predispose those same subpopulations to lose out from technological advances due to greater barriers to adoption. Conversely, those initially endowed with greater resources and power can more effectively block scientific advances that might cause them welfare losses. Solidarity mechanisms – e.g., social protection programs, formal and informal safety nets – are therefore essential complements to technological advance so as to ensure true Pareto improvements, not just *potential* net gains. Over the middle third of the 20th century, rapid scientific advances combined with expanded employment, food assistance, and other social protection programs targeted to the poor generated both a sharp increase in crop yields and a marked reduction in hunger in the US and other HICs.

Rapid agricultural and food security progress in the HICs did not, however, protect LMICs in Africa and Asia from massive famines from the 1940s through the World Food Crisis of the early 1970s. Indeed, rapid population growth led scholars to predict looming worldwide famine (Ehrlich 1968). But once again, the potent combination of science and solidarity with the poor generated responses that not only avoided famines but ushered in a period of unprecedented economic and agricultural productivity growth worldwide. The 1960s-70s Green Revolution in Asia and Latin America exceeded even the progress seen in the HICs a generation or two earlier, as increased R&D investment drove up staple crop yields and enabled a rapidly growing population to consume more calories and protein. The rapid development and diffusion of high-yielding varieties of maize, rice and wheat, and of inorganic fertilizers, irrigation, and machinery, fueled rapid productivity growth. This brought down real food prices sharply, improving calorie and protein access among the poor, reducing deforestation for agricultural expansion, and sparking economic growth (Evenson and Gollin 2003; Pingali 2012; Gollin et al. 2018).

As important as the technological advances were, historically unprecedented food supply growth was insufficient to meet the looming food security challenges. Amartya Sen and others emphasized the importance of individual entitlements, sparking a contemporaneous diffusion of social protection measures that, combined with technological advances, had huge effects. After all, poverty, not agricultural productivity, is the key driver of food insecurity. As Sen (1981, p.

1) so powerfully put it in the opening sentences of his seminal *Poverty and Famines*, "[s]tarvation 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" (emphasis in original). The result was the steady growth of food assistance, cash transfer and employment guarantee schemes, adapting the New Deal interventions to varied settings internationally. Humanitarian aid professionalized rapidly, increasingly decoupling from the donor supply-driven, surplus disposal designs of 1950-70s era food aid programs to needs-based food assistance (Lentz et al. 2013). By the mid-2010s, more than 130 LMICs had fielded at least one non-contributory cash transfer program (Bastagli et al. 2019). More remarkably, in the short interval from March-July 2020, 200 different countries/territories announced and/or implemented 1,055 different social protection measures in response to the massive dislocations caused by the COVID-19 pandemic (Gentilini et al. 2020).



Data source: FAOStat

Figure 1: Global population undernourished, 2000-2019

The combination of significant investment in cutting-edge science to drive productivity growth on the supply side, plus expanded social protection on the demand side to ensure that the poor could benefit from more bountiful harvests, led to a period of unprecedented food security improvements. The world's population grew from 2 billion people in 1928 – through 3 billion in 1960 and 4 billion in 1975 – to 7.8 billion today. Yet today 5 billion more people enjoy adequate daily calorie intake than when the Great Depression began. Think for a moment about that remarkable accomplishment. Each year since 2000 almost 90 million additional people have gained access to adequate dietary energy to maintain an active life, even though the absolute number of undernourished persons has fallen quite slowly (Figure 1). That is equivalent to 10,000 extra people meeting their caloric requirement every hour for two decades because AVC advances could fully absorb the added demand arising from population growth.

To be clear, the hunger problem remains far from fully resolved. The number of undernourished has unfortunately grown by about 60 million people since 2014, after decades of steady decline, for reasons I discuss below. But over the same period, population growth has meant that the number *not* undernourished has grown by about 450 million persons over that same period. We must not neglect the successes as we redouble efforts to attend to ongoing needs.

These successes had unintended consequences and induced complacency that sowed the seeds of tomorrow's challenges. As famines seemed a tragedy relegated to history, growth in agricultural R&D slowed markedly from the mid-1970s through the late 2000s, especially public investments in the HICs and in Sub-Saharan Africa (SSA) (Beintema and Elliott 2009). Because agricultural pathogen and pest pressures evolve continuously, especially in the face of anthropogenic climate change, slowing R&D investment spelled trouble, because it slowed productivity, and thus supply, growth.

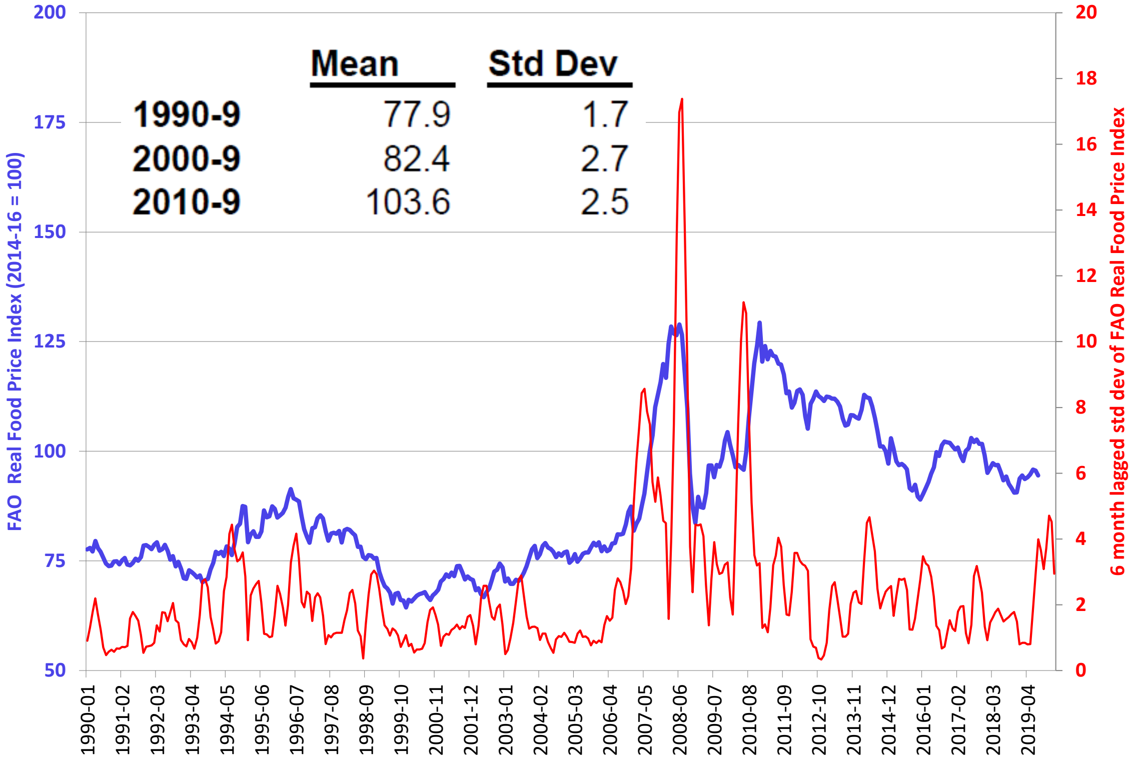


Figure 2: FAO Real Food Price Index, January 1990 – July 2020

Somewhat predictably, but with a lag, real (i.e., inflation-adjusted) food prices began to increase. After hitting an all-time low in 1999, the FAO food price index began to creep steadily upwards until it spiked in 2007-8, collapsed with the onset of the Great Recession, then spiked again from late 2009 through 2011 (Figure 2). This led to a jump in global poverty and food insecurity. Higher food prices also induced new investment in agricultural R&D and land, and sparked food riots in dozens of countries worldwide (Barrett 2013). Prices have settled somewhat in the intervening decade, but real prices remain roughly 25 percent higher today than the 1990s average.

Predictable dietary consequences also followed from the heavy emphasis on addressing hunger by increasing calorie and protein supplies through starchy staples in both agricultural R&D and in food assistance programs. Given faster TFP growth in staple cereals, roots and tubers, the price of micronutrient-rich fruits, legumes, pulses and vegetables rose relative to that of staples in many places (Pingali 2012). Cheaper calories and protein naturally led to changes in food processing and diets. The dietary diversity of increasingly well-off consumers suffered from the resulting negative substitution effects that worked against the positive income effects of lower overall real food prices and higher real incomes. At the same time, rising real wages fueled demand for convenience in the form of processed and ultra-processed foods and food prepared (by others) and consumed away from home. Food processors, manufacturers, retailers and food service firms sought greater market share and profit by supplying foods high in unhealthy fats, salts and sugars (Barrett et al. 2020). Diet is now the top risk factor for morbidity and mortality globally, with high intake of sodium and low intake of whole grains and fruits the leading dietary risk factors for deaths and disability globally (GBD 2019). The resulting global obesity crisis has been especially problematic in the middle-income countries, which account for more than 70% of all overweight and obese people worldwide (Shekar and Popkin 2020), leaving LMICs facing an increasingly complex, triple burden of malnutrition: undernourishment, combined with micronutrient deficiencies, as well as obesity (Gómez et al. 2013).

Even though staple crop TFP growth relieved some agricultural extensification pressure on forests (Gollin et al. 2018; Pelletier et al. 2020), agricultural development focused on staples and livestock nonetheless expanded the agricultural frontier in LMICs. USDA ERS data indicate that agricultural lands expanded at an average annual rate of 2.6 percent from 2005-16 in SSA. Agricultural innovations also led to rapid expansion of water use in irrigation. FAO AQUAStat data indicate that agriculture accounts for 70 percent of total human water withdrawals today, and more than 80 percent in Africa and Asia, where key river basins suffer serious water stress. This underscores the pressing need for increased economic research on the agriculture-poverty-water nexus (Balasubramanya and Stifel 2020). Further, agri-food systems now account for roughly one-quarter of all greenhouse gas emissions, thereby contributing to climate change that increases water stress on those systems, and on humankind more broadly (IPCC 2019).

The Coming Decades' Five Big Challenges

The gains of the past century's scientific and social protection advances are very real. But they have largely run their course. We must now shift focus and break from the decades-old strategy of emphasizing agricultural yield growth to expand calorie supplies and reduce hunger. Five major challenges loom that necessitate shifting our innovation strategy. And because public and private decision-makers inevitably manage to what we measure, this also implies shifting the metrics we use to gauge progress (or lack thereof), placing greater emphasis on sustainable increases in dietary quality and total factor productivity to stop focusing solely on yields and dietary energy.

Hunger Is Now Primarily a Conflict Resolution and Humanitarian Response Problem

Despite the herculean efforts of prior generations of scientists, policymakers, farmers and other agri-food system actors, hunger indisputably remains a blight on humankind. The number of undernourished people – those who cannot access sufficient dietary energy (i.e., calories) to maintain an active and health life, which manifests biochemically in the physical sensation of hunger – has been rising since 2014. The most recent estimates from the United Nations agencies are that just under 700 million people were undernourished in 2019 (FAO et al. 2020).

But hunger today is less a food systems problem than ever. Hunger is increasingly concentrated in a shrinking number of places plagued by a lethal combination of conflict, environmental stress, and weak governance, so-called fragile settings. Populations in fragile settings face recurring food crises that have permanent consequences for human flourishing, most commonly manifest in severe acute malnutrition (SAM) in the short-run and in stunting – i.e., abnormally low height for age – in the longer-run. Over the past two decades, conflict-affected countries' share of stunted children grew from 46% to 75% (FAO et al. 2017). In 2019, of the 216 million people assessed to need humanitarian food assistance globally, 57% lived in just 10 countries, 8 of them in conflict (Afghanistan, the Democratic Republic of Congo, Ethiopia, Nigeria, South Sudan, Sudan, Syria, and Yemen), and the other two (the People's Democratic Republic of Korea and Venezuela) facing major governance crises (Development Initiatives 2020). The spatial concentration of hunger in fragile settings that routinely suffer protracted, complex emergencies arises in part due to the strong positive association between rising temperature, severe drought and other natural disasters, and conflict (Barrett 2013; Hsiang et al. 2013; von Uexkull et al. 2016). The resulting food emergencies inevitably spill over into other countries, due especially to a record 80 million people globally who have been forcibly displaced from their homes as of end-2019 (UNHCR 2020). This is especially worrisome because the population of fragile settings is expected to grow rapidly, from about 1.8 billion today to 2.3 billion by 2030 (OECD 2018).

Unfortunately, although they have become far more professionalized over the past 20-plus years, humanitarian response systems remain woefully underfunded and structurally inadequate to the task (Lentz et al. 2013; Maxwell et al. 2020). And without better social protection response, acute food insecurity helps foster more sociopolitical instability in a vicious cycle of reinforcing feedback (Barrett 2013).

Especially with historically low borrowing costs, the world today needs to invest more to address humanitarian disasters. More than ever, disasters inevitably spill over across borders, in myriad ways – economic, epidemiological, political and social. Our choice is to pay now versus pay later to address humanitarian needs, unless we are prepared to pay probably even more to erect more effective institutional and physical barriers to the cross-border transmission of humanitarian problems. Our predecessors tried that approach a century ago, erecting unprecedentedly strict immigration and trade barriers that ultimately aggravated the Great Depression, sowed international distrust, and helped foment unrest that turned into World War II. It seems far wiser to invest up front in addressing global humanitarian issues than to futilely ignore or attempt to wall ourselves off from such problems, which most tangibly manifest in pockets of SAM.

Domestic safety nets are likewise essential. The televised spectacle of everyday Americans waiting hours in long lines for food pantry rations during the COVID pandemic stunned viewers. This is partly due to underfunded social protection programs, such as the Supplemental Nutrition Assistance Program (SNAP, still often known by its old moniker as food stamps) and the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC). Virtually all experts favor expanding SNAP and WIC, which offer high returns on investment because they provide an essential safety net for those who fall on hard times (Gundersen and Ziliak 2018; Gundersen 2019; Schanzenbach 2019). Most nations recognize this, as evidenced by the remarkably widespread responses of governments in expanding social protection schemes in response to the COVID-19 pandemic's severe livelihoods disruptions (Gentilini et al. 2020). This is the appropriate first-order policy response to a massive demand side shock to food systems (Barrett 2020).

The point is that, unlike 90 or 50 years ago, today's and tomorrow's hunger crises are fundamentally humanitarian and conflict resolution issues, not agri-food systems problems, and most certainly not agricultural production problems. The world has repeatedly registered record cereals harvests as hunger as ticked upwards the past few years. The root cause of hunger is poverty, which traces back to corrupt and incompetent governance, the absence of reliable and accessible social protection programs, and most seriously due to recurring violent conflict (DeWaal 2017; Runge and Graham 2020) that disrupts the individual livelihoods, agro-input distribution, and post-harvest food distribution on which food security depends. To address hunger, we need humanitarian and conflict resolution innovations, not agri-food ones.

Healthy Diets Are Today's Primary Agri-Food Systems Challenge

The core nutrition-related agri-food systems issue today is access to healthy diets. We do not even have data that enable us to estimate the number of people who suffer deficiencies in one or more essential nutrient. Single nutrient estimates – e.g., for iron or vitamin A – suggest that 3-3.5 billion people, but perhaps more, lack one or more essential nutrient. That is 4-5 times the number of undernourished people (Gómez et al. 2013), reflecting the fact that the most affordable nutrient-adequate diet exceeds the cost of adequate dietary energy by a factor of 2.7 (Bai et al. 2020) and that few people make dietary choices to minimize the cost of a fully healthy diet. At the same time, the number of overweight or obese people now exceeds two billion globally. Globally, one in five deaths are associated with poor diet, especially due to low intake of whole grains and fruits and excessive sodium intake (GBD 2019).

Where reducing hunger and undernourishment was the primary agri-food systems challenge of the 20th century, now it is to facilitate universal access to healthy, non-obesogenic diets. Every region in the world has ample supplies of carbohydrates and protein. Diet-related health problems arise due to excessive carbohydrate intake and/or shortfalls in intake of essential micronutrients, dietary fiber, and other bioactive compounds (e.g., carotenoids, flavonoids; Poole et al. 2020). Especially with climate change, these patterns are unlikely to change without concerted agri-food systems innovations (Nelson et al. 2018; Haddad 2020).

The core problem is that healthy diets are unaffordable to an estimated three billion people globally, with affordability lowest in SSA, mainly due to the relatively high cost of fruits and vegetables (Hirvonen et al. 2019; Bai et al. 2020; FAO et al. 2020).[6] But income growth

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[6] This is not just a LMIC problem. Gundersen et al. (2019) estimate that in 99 percent of US counties SNAP benefits do not cover the average costs of even lowest cost nutritionally adequate (USDA Thrifty Food Plan) meal, which, at just $2.36, exceeds the maximum SNAP benefit per meal of $1.86 by 27 percent.

among the poor is only a partial solution to the problem of access to affordable healthy diets. Relative prices, marketing campaigns for unhealthy foods, and the demand for convenience and storability – which often tradeoff healthful attributes – routinely induce unhealthy food choices by those who could afford a healthy diet.

A complementary strategy involves R&D targeted at growing the relative supply of nutrient-rich commodities, and at improved – and better regulation of – food processing and manufacturing practices (e.g., less disposal of bran in milling, healthful food reformulation) so as to drive down the price of healthy foods, including relative to less healthy ones. There is also a role for shifting relative prices through food subsidies and/or taxes to internalize public health externalities, like the range of sugar-sweetened beverage taxes that have gained popularity and established their effectiveness in many places (Allcott et al. 2019; Shekar and Popkin 2020). And in-kind food assistance programs must emphasize healthy commodities (e.g., nutrient-rich fruits, legumes, nuts, vegetables, and whole grains) and discourage excessive intake of sodium, sugars, fats and ultra-processed foods of various sorts.

Pay more attention to Africa

Demand growth due to rising population and incomes, along with urbanization, are key drivers that alarm observers about future food security. These phenomena all concentrate disproportionately in SSA. Scholars', policymakers' and investors' attention must concentrate far more on Africa than it has to date.

The geography of human populations will shift markedly over the rest of this century. First, the world became majority urban in 2007 and by 2050 68 percent will live in cities (UN World Urbanization Prospects 2018). This necessarily means increasingly elongated supply chains from rural breadbasket areas. And the COVID-19 pandemic has increased the premium retailers, food service providers (e.g., farm-to-table restaurants), and consumers (e.g., community supported agriculture subscribers) place on short supply chains. This matters more in African and Asian LMICs than in the HICs because mega-cities are far more common in the former.[7] Mega-cities create greater gravitational pull favoring urban and peri-urban producers serving massive

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[7] Among OECD member states, only Korea (three), Australia, Japan and the US (two each) have multiple cities of three million or more people. By contrast, China has more than 30, India 10, Pakistan 5, and Brazil, Egypt, and Nigeria have 3 each (Barrett et al. 2020). Population distributions are more spatially polarized in today's LMICs.

concentrations of consumers, especially if they can take advantage of economies of scale or scope in production and distribution.

Second, the best recent projections forecast global population peaking in the 2060s at roughly 9.7 billion people, an increase of roughly one-quarter over today's 7.8 billion (Vollset et al. 2020). Even more striking, however, Vollset et al. (2020) predict that SSA will add approximately 2 billion residents by the end of the century, overtaking Asia as the most populous continent. Indeed, by 2100, Africa will be the only world region recording net population growth. Populations in Europe and east Asia, by contrast, have already peaked or will peak this decade. Because more than 70% of food is eaten in the country in which the source commodity was grown (D'Odorico et al. 2014), spatial patterns of population growth compel increased attention to African agri-food systems. Continuation of the recent trend towards tightened immigration restrictions in OECD countries will likely only reinforce this pattern.

Income growth patterns will reinforce demographic drivers to compel a focus on Africa. Over the 2010s, real GDP per capita grew faster than the world average in SSA and is broadly expected to continue that more rapid growth, partly due to the demographic dividend described above. Because SSA is also the world's lowest-income region, its income elasticity of food demand is higher than elsewhere. The combination of a higher income elasticity of demand for food, faster income growth, and faster population growth implies, by my back of the envelope calculations, that Africa is likely to account for at least half, and likely more than 70 percent of food demand growth worldwide between now and 2100. That will inevitably draw heightened industry focus on the region. Given that SSA also has the world's lowest agricultural TFP (Fuglie et al. 2019), the opportunities for innovation-based advances are especially rich in Africa.

Beyond farm to agri-food value chains

Most observers know that agriculture's share of total economic output (GDP) falls over time as incomes grow. Fewer appreciate that the share of total consumer food expenditure that accrues upstream to farmers (and their input supplies) likewise falls steadily with income growth (Barrett et al. 2020; Yi et al. 2020). Yi et al. (2020) show that for 61 middle- and high-income countries that accounted for about 90 of global economic output in 2017, the average post-harvest AVC share of consumer food expenditures was 73 percent in the 2005-15 period. Since they account for most value addition, traders, processors, manufacturers, retailers, restaurants, etc. increasingly drive behaviors throughout the agri-food system. Therefore, public policy and consumer behavior must align firms' incentives with broader societal objectives, such as affordable, healthy diets, safeguarding basic human rights, and protecting the planet. For-profit firms respond, especially if there is money to be made in solving problems, and/or if strategies that impose negative environmental or health externalities incur heavy costs.

AVC actors faced with appropriate (food or capital) market and/or regulatory incentives can be engines for helpful innovation. For example, commercial industrial salt iodization has largely remedied iodine deficiencies that were the world's primary cause of irreversible brain damage and mental retardation less than fifty years ago, proving one of the world's most cost-effective public health interventions. Conversely, incentives can drive AVC actors to degrade food quality, as when processors mill grains to remove nutrient-and-fiber-rich bran and germ in order to increase product shelf life and reduce manufacturing costs for flour-based foods, or when manufacturers or food service firms add fat, salt or sugar to heighten sensory satisfaction. We need to pay as much attention to the incentives AVC intermediaries face as those farmers do.

As incomes grow and populations urbanize in the years ahead, the role of AVC actors will only grow further. But their incentives will also increasingly turn on foods' non-nutritive attributes that enable firms to compete on terms other than price: convenience, customization, freshness, geographic indications, pan-seasonal availability, network externalities associated with product standards, and credence attributes such as the brand's environmental, health and justice claims (Barrett and Yang 2001; Swinnen et al. 2015; Barrett et al. 2020). Demand for such attributes is generally more income responsive and less price responsive than is demand for nutrients in food, so firms seek profits by meeting evolving consumer demands.

This has three big implications. First, this will drive supply chains to grow both more globalized – e.g., to overcome seasonality constraints – and more localized – e.g., to maximize freshness and verification of product claims. The demand for variety will support polycentric AVC evolution. Second, in an effort to win over more lucrative consumers – and pre-empt costly regulation – post-harvest AVC firms will increasingly impose detailed processes on primary producers. We already see this as major companies such as Campbell's Soup, Cargill, Nestle, PepsiCo, Smithfield Foods, Walmart, etc. write soil health or labor requirements into supplier contracts. Third, as consumers, employees and investors increasingly value products' credence attributes, trust grows ever more important. This puts a premium on novel methods to resolve information asymmetries so as to verify firms' claims and reputational mechanisms that enforce claims ex post of transactions.

Rising opportunity cost of land

For most of human history, food supply growth entailed bringing more land into cultivation or pasture. That changed beginning with the English enclosure movement of the late 18th century, and then accelerated due mainly to mechanization, irrigation, and improved genetic and chemical inputs over the course of the 20th century. The steadily falling factor shares of land in agricultural production have followed naturally from rising opportunity costs of land as population and income growth stimulated demand for residential space and supporting public infrastructure, and as manufacturing and services growth fueled land demand in those sectors. The global agricultural land footprint nevertheless increased 10 percent, 1961-2006, concentrated in the LMICs, as the HICs saw a 9 percent decline in agricultural land area, especially since the mid-1980s peak in farmland in Europe and North America (Fuglie 2010). In the past decade, USDA ERS data suggest that land use in agriculture has slowed to near zero in LICs/MICs outside SSA, where agricultural lands continue to expand by roughly 3% per year, on average.

The opportunity cost of land will continue to rise steadily. This will occur for some of the same historical reasons, especially in SSA, as rapid population growth will further expand cities and towns, while structural transformation out of agriculture will expand the non-farm footprint.

Mainly, however, the opportunity cost of land will rise for environmental and health reasons. Heightened popular appreciation of the climate crisis has forced recognition that agriculture – perhaps especially due to land conversion – is a major source of harmful CO_2, CH_4, and NO_2 greenhouse gas (GHG) emissions, even though the sector could instead be a GHG sink with greater sequestration in cover crops, soils and trees (IPCC 2019). That conversion takes on greater urgency with each extreme weather event attributed, rightly or wrongly, to climate change. The emergence of carbon credits and emissions trading systems (ETS), various payments for ecosystem services (PES) schemes, public conservation subsidies, and contractual incentives from downstream AVC firms all help to incentivize increased use of agricultural lands for GHG sequestration and related ecosystem services.

The climate crisis is also accelerating transitions from fossil fuels to renewable energy sources. Expanded wind, solar and geothermal energy production will require converting more land into renewable power generation. As rapid advances in these technologies drive down capital costs, installation grows more financially attractive, especially in areas already on the power grid and/or near cities, limiting connection costs and power transmission losses.

Meanwhile, the still-underrecognized mass extinction crisis now underway is driven largely by the combination of climate change and habitat loss, mostly due to agricultural land conversion in LMICs (IPBES 2019). Reducing, or even reversing, agricultural land conversion will become more attractive in so far as the income elasticity of demand for biodiversity conservation increases with a nation's wealth and almost certainly exceeds the income elasticity of demand for food (Jacobsen and Hanley 2009). Land conservation is also intrinsically important to agriculture so as to protect pollinators, and reduce flood risk, nutrient runoff and soil erosion that all impact crop, fisheries and pasture productivity (Winfree and Bartomeus 2011; Schilling et al. 2014). We should therefore anticipate increased market demand for habitat and biodiversity conservation, although externalities imply that market demand will fail to capture all the benefits of reducing agriculture's terrestrial footprint.

Most recently, pandemics – SARS, Ebola, and now COVID-19 – have heightened awareness of the infectious disease dangers that follow from agricultural land conversion, especially those due to zoonoses. Since 1940, agricultural drivers – mainly extensification into forests and wetlands – were associated with more than 25% of all — and more than 50% of zoonotic — infectious diseases that emerged in humans (Rohr et al. 2019). A key mechanism is that anthropogenic land conversion increases the density of zoonotic host species in contact with humans, i.e., species that vector a broader number of dangerous viruses typically outcompete non-host species in converted lands (Gibb et al. 2020). The rising one health/planetary health movement increasingly demonstrates the need for expanded buffer lands between wild virus reservoirs and humans (Myers and Frumkin 2020).

The net result of these various trends is growing demand for rural lands to produce energy or environmental services rather than agricultural commodities. Those demands will grow especially great in sunny drylands and tropical regions with greater renewable energy, GHG sequestration, and biodiversity conservation potential and lower opportunity cost of land in agricultural production. That could include large spaces in Africa and Asia.

The challenge is that converting land from agriculture into environmental and energy services generates positive externalities that have proved difficult to monetize for land managers, not least of which because the climate and extinction crisis and zoonoses control are all global public goods. The complex political economy of carbon taxes, credits and ETS, for example, has resulted in a current global average carbon price of only US$2/tCO2, with less than five percent of GHG emissions covered by a carbon price within the US$40–80/tCO2 range the High-Level Commission on Carbon Prices estimated is necessary to cost-effectively reduce emissions in line with the temperature goals of the Paris Agreement (HLCCP 2017; World Bank 2020).

Rising and Shifting Risks

Risks of extreme weather events due to climate change, of pandemics due to anthropogenic land conversion, and of permanent displacement due to sea level rise are all growing (Hauer et al. 2019; IPCC 2019; Gibb et al. 2020). Many of these risks are likely to rise with continued agricultural development based on land conversion and imprecise application of biochemical inputs such as antibiotics, fertilizers, and pesticides (Rohr et al. 2019). They are also correlated with conflict risk. Uninsured risk is a primary cause of poverty traps, so rising and shifting risks increase the likelihood of rural subpopulations collapsing into chronic poverty (Barnett et al. 2008; Barrett and Santos 2014; Barrett et al. 2019).

Recent years have also brought a growing backlash against globalization, manifest in trade restrictions suddenly enacted by dozens of governments on both agricultural exports and imports. Combined with the upward pressure on prices generally over the past twenty years, this has translated into appreciably greater global agricultural commodity price volatility (Figure 2).

Rising and shifting risks facing agri-food systems puts a premium on technological innovations to help manage risks better but also on solidarity mechanisms to transfer risk from the unlucky and vulnerable to the lucky and secure. Improved animal and plant genetics, soil and water management, and other on-farm innovations offer key means of risk reduction. Financial, institutional, and policy innovations to help reduce and distribute risk more efficiently will be equally crucial going forward. Furthermore, reliable and timely information is of increasing value in assessing and managing increasing risks, just as it is in capturing the growing demand for foods' credence attributes.

Social-technical bundles as combinatorial innovation

Breakthrough innovations are almost always combinatorial, clever means of combining prior discoveries in order to meet emergent societal needs, rather than truly *de novo* discoveries that do not build on prior innovations (Arthur 2009). As I have already emphasized in discussing past successes, addressing food security challenges invariably requires a combination of both scientific advances that enhance agri-food system TFP and sociocultural change or policy measures that foster solidarity among people.[8] Even as Herrero et al. (2020) enumerate scores of promising new scientific and engineering advances with the potential to transform agri-food systems, they especially emphasize eight social and institutional factors as "essential elements for accelerating the systemic transformation of food systems" (p.270). We must get the institutions and policies right in order for the science – and associated financing – to follow and enable technology diffusion to achieve real transformations at scale.

In this final section, I emphasize five key agri-food system innovation domains for the coming decades if we are to meet the global food security challenges that lie ahead. In doing so, I call attention to the central importance of "socio-technical bundles" – the combinations of scientific advances and acts of social solidarity – that are likely essential to progress in a wealthier, warmer, more urban, populous, land-scarce, shock-prone, and African world in which post-farmgate firms increasingly drive agri-food system behaviors and performance.

Agricultural R&D

Rising food demand growth must be met through TFP growth and increased capital investment. The world can afford neither a new round of price spikes that drive millions into poverty and food insecurity nor continued conversion of natural lands into agriculture, given the climate and extinction crises. And it is unrealistic to expect an influx of labor into agriculture. So perhaps the most obvious imperative for the years ahead is to re-accelerate and re-orient agri-food systems R&D investment. Especially high priorities are for philanthropic and public funding to ensure open access to discoveries that focus more on Africa, on nutrient-rich fruits, nuts and vegetables, and on post-farmgate processes. But science alone will not suffice.

The case for increased R&D investment is straightforward. Agricultural R&D already underway shows considerable promise to at least partly address some of the challenges ahead.

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[8] This point – like most everything in this essay - is not original to me but rather integrates others' prior findings, reinforcing Arthur's (2009) emphasis on the combinatorial fundamentals of useful innovation.

There has been major progress over the past decade or so in single crop traits, such as biofortification (Bouis and Saltzman 2017), stress tolerance (Steinwand and Ronald 2020), transgenic pest resistance (Qaim 2016, 2020), and improved photosynthetic efficiency in plants (Simkin et al. 2019; López-Calcagno et al. 2020). Recent advances in genomic and synthetic biology tools (e.g., gene editing, biosensors, designed nucleic acid systems) promise to accelerate and broaden the scope of genetic advances in crops and livestock. In particular, these emergent methods and technologies show considerable promise in addressing the environmental and health shortcomings of Green Revolution era plant and livestock technologies (Qaim 2020). So there are reasons for optimism based on the scientific research already underway.

Historically, the returns to agricultural R&D have been exceptionally high, indicating systematic underinvestment relative to alternative uses of scarce funds. Pardey et al. (2016a) estimate mean (median) internal rates of return, 1975-2014, of 42 (35) and 62 (38) percent in SSA and the rest of the world, respectively, a clear sign of underspending. The food systems impacts of R&D are clearly reflected by Hertel et al.'s (2020) finding that from 1991-2011 direct R&D investments in SSA were the main driver of lower food prices in Africa, not trade and not the adoption/adaptation of technologies developed via R&D elsewhere. If affordable, healthy diets are a first-order objective in meeting the coming global food security challenge, then increased agri-food R&D is plainly an instrument of primary importance, especially for Africa. Combined with borrowing costs that presently sit at historic lows, the world is awash in capital seeking attractive returns of the sort that agricultural R&D has long delivered.

Indeed, the returns to agri-food research increase further when we recognize their role in insuring against temporal uncertainty (Cai et al. 2017). Given the long lags between R&D expenditures and agri-food market impacts at scale, as well as the considerable temporal uncertainty in climate, demand, and supply projections in the absence of technological advance, R&D holds option value. This is especially valuable because food price series are positively skewed due to their storability (Williams and Wright 1991). Excessive stinginess in agri-food R&D investment therefore increases the risk of future food price spikes, with potentially calamitous impacts on food security. Cai et al. (2017) show that this uncertainty implies a need to sharply accelerate public R&D spending relative to estimates that ignore uncertainty, especially for places such as Africa where future uncertainty – especially around population and income growth rates – is especially great.

But we cannot merely replicate agricultural R&D patterns of the past. First, agricultural R&D increasingly needs to aim to mitigate the adverse effects of climate change on productivity growth (Hertel and de Lima 2020). Anthropogenic climate change has been a strong headwind in the face of technological change, reducing global agricultural TFP growth by an estimated 21% since 1961, equivalent to losing roughly a decade's productivity growth (Ortiz-Bobea et al. 2020). Climate adaptation research is required not only to adapt to warming temperatures, but equally to increased risk of drought, flooding (especially with sea water), and to pathogens and pests whose ranges are shifting, i.e., to abiotic and biotic shock resistance and stress tolerance. Even in temperate zones where warmer temperatures should physiologically stimulate more rapid crop growth, because warming also changes pathogen and pest pressures, climate change increasingly compels defensive (e.g., pesticide, weeding labor) investments by small farmers to protect crops, generating costly tradeoffs with productivity-enhancing inputs such as inorganic fertilizer or improved seeds among liquidity constrained small farmers (Jagnani et al. forthcoming).

Driving down the real and relative prices of healthful foods such as fruits, legumes, nuts and vegetables will require significant expansion of R&D directed towards these products, not just doubling down on traditional focal cereal, livestock, root and tuber commodities (Nelson et al. 2018; Mason-D'Croz et al. 2019; Haddad 2020). Expanding the per capita supply of healthful foods will also require significant reallocation of lands from starchy staples and feed to more nutrient-dense commodities (Sanchez 2020). We must stop treating horticultural crops as "specialty crops", as if they aren't absolutely central to delivering a healthful food supply.

Agri-food R&D must also increasingly attend to farm- and landscape-scale cropping systems change rather than just to single species. Most animal and plant genetic improvement efforts focus on improving individual plants through some form of biomimicry, finding and replicating or adapting solutions found elsewhere in nature. Weiner (2019) makes a powerful argument that the most promising opportunities to promote higher-yielding plant genotypes will rely not on selection and ecological engineering for improved plant-level productivity but, rather, for greater population performance that comes expressly at the cost of individual plant fitness. He argues that the semi-dwarf varieties at the heart of Green Revolution advances were "due to inadvertent group selection" as pure stands of shorter stature varieties could thrive and generate higher plot-scale yields but would have been selected out had they been interspersed with taller varieties that would outcompete them for solar energy. Especially with monocultures' increasing vulnerability to pests and diseases (Fones et al. 2020), R&D needs to work more on polycultural mosaics that preserve, or even advance, agrobiodiversity. For example, crops bred to "waste" scarce energy by fixing atmospheric nitrogen and accessing water deeper underground through long root systems can generate significant positive spillovers for other plants and the planet, at the cost of stalk-level edible biomass in those specific commodities. As I discuss below, Weiner's (2019) point about targeting population-level performance, not just individual performance, applies more broadly to policy and the institutions that govern community life, not only to promoting animal and plant productivity through R&D.

R&D for affordable, healthy diets will also increasingly require advances in off-farm products and processes. Many of these can be enabled by lower-cost renewable energy and digital technologies, points to which I return to below. As energy and information costs continue to fall, for example, indoor, vertical farming of horticultural crops using aero/aqua/hydro-ponic methods in urban/peri-urban settings inevitably becomes more commercially viable, magnifying the need for R&D to tailor varieties to these unnatural environments (Pinstrup-Andersen 2018; Beacham et al. 2019). The same goes for improved food preservation and cold chains to facilitate farm-to-market intermediation of fresh and whole foods, e.g., solar-powered cooling for value chains to reduce post-harvest nutrient loss and safeguard food safety. More progress can be made to improve diet quality by investing in technologies that help lower both the real and relative prices of healthy foods than by inherently zero-sum price policies or by consumer behavioral change communications efforts.

We also need significant shifts in the geography of agricultural R&D, which has lagged badly over the past generation in both Africa (and other LICs) and HICs, while growing significantly in middle-income Brazil, China and India. Public R&D in MICs has now overtaken that in HICs and both groups' R&D dwarfs research spending in LICs, especially in Africa (Pardey et al. 2016b). China now outspends the US in both public and private agri-food R&D (Chai et al. 2019). Agroecosystems exhibit huge heterogeneity, so place-specific R&D is essential. Given that most growth in food demand will take place in Africa, and we can only rely so much on trade to meet expanding demand, a growing relative share of expanding agri-food R&D needs to occur in SSA.

Agricultural R&D has also increasingly shifted to the private sector, especially but not exclusively in HICs (Pardey et al. 2016b). 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). Many of the most promising innovations on which future agri-food systems will depend - especially in digital innovations and de-agrarianized food production systems discussed below - rely overwhelmingly on private finance. If private financing ties up discoveries in complex intellectual property (IP) issues, it will retard diffusion and diminish the impact potential of technological advances.

This last point underscores how simply pushing more money at yawning R&D needs is unlikely to deliver much. Consider the cautionary tale of "golden rice," the transgenic variety that biosynthesizes beta carotene, a remarkable scientific discovery aimed at addressing the prevalence of vitamin A deficiency among poor rice-eating populations worldwide.[9] The US Patent and Trademark Office recognized golden rice with its 2015 Patent for Humanity Award. But the discovery of this breakthrough was first published in 2000 (Ye et al. 2000). Twenty years later, despite great fanfare and scores (if not hundreds) of millions of dollars in follow-on investment, golden rice still has not been approved for commercial cultivation and sale in a developing country. It has faced myriad hurdles associated with IP licensing, national biosafety and food safety regulations, environmental activists mobilized in opposition to this and other genetically modified organisms, etc. Juxtapose the golden rice case with that of the IR8 and IR64 varieties originated in 1966 and 1985, respectively, by the International Rice Research Institute. These were arguably far less noteworthy scientific advances than golden rice, yet the semi-dwarf IR8 was the first "miracle rice" of the Green Revolution and the third generation IR64 became purportedly the most widely diffused cereal seed variety in history. The difference in impacts between IR8/64 and golden rice arose less from scientific differences than due to social ones. In the face of broad popular distrust of genetic engineering, and active – sometimes violent – opposition from environmental groups, and faced with a dense thicket of patents and diverse national regulations to navigate, golden rice diffusion has been far slower and more costly than for the earlier rice varieties developed using conventional plant breeding methods and public R&D and extension funding in an environment more trusting of science, and less reliant on private finance and IP protections. Advances in genetics (or any other scientific field) are

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[9] This paragraph draws extensively on Regis' (2019) excellent discussion of the golden rice experience.

insufficient to ignite systemic change. Social innovations must accompany R&D to make investments in technological advances impactful.

The absence of enabling sociopolitical innovations helps explain why TFP gains per real dollar of agricultural R&D have been steadily declining, by an average annual rate of 3.7 percent from 1970 to 2007 (Bloom et al. 2020). One likely partial explanation is that prior research tackled many of the lowest cost high-return options, i.e., there may be intrinsically diminishing returns to R&D over time. But the declining cost-effectiveness of agricultural R&D also clearly underscores the need to address sociocultural and political obstacles to both inducing appropriate scientific research and to enabling promising innovations to diffuse and scale. R&D investments must be matched with institutional and policy change to unlock the potential of scientific advances to meet the global food security challenges ahead.

One problem is the complex political economy of agricultural biotechnology, which has deep roots in scientific illiteracy and resulting political activism in the broader population (Herring and Paarlberg 2016; Fernbach et al. 2019).[10] The result has been overly burdensome regulation, especially in Europe, most of SSA, and parts of Asia (notably, India), that impedes field deployment and upscaling of advances arising from agricultural biotechnology (Qaim 2016, 2020; Steinwald and Ronald 2020). A notable consequence is that biosafety and food safety concerns differentially retard genetic improvement and reformulation of agrichemicals and foods relative to advances in digital and mechanical technologies, with the predictable result that the latter innovations attract wildly disproportionate private investment in agricultural R&D today.

A further complication arises from IP regimes that loom increasingly large in influencing the pace and directions of research as the share of private agri-food R&D increases. To be sure, private R&D is desirable, indeed essential, and IP protections are necessary to induce more private investment. But patent systems are increasingly broken, discouraging the sorts of innovation society needs (Jaffe and Lerner 2011). In the agri-food space, changes in IP law have substantially complicated R&D, most notably following the 1980 Chakrabarty decision by the US Supreme Court that for the first time permitted patenting a living organism. Strategic hold-

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[10] Fernbach et al. (2019) find that in a nationally representative sample of US adults, extremity of opposition to genetically modified foods is greatest among those respondents who have both the weakest objective understanding of science and genetics and the strongest confidence in the veracity of their (mistaken) beliefs. They replicated their findings in France and Germany, so this is not just an American phenomenon.

ups and patent thickets drive up costs and slow progress as private R&D becomes more dominant (Schimmelpfennig 2004; Jaffe and Lerner 2011). Solutions are available, as manifest in the Open COVID Pledge launched in April 2020 to enable biomedical innovators to make their IP widely available free of charge, following a model based on those used for open-source software; the pledge covered more than 250,000 patents worldwide by the end of July 2020 (Contreras et al. 2020). Innovations to patent law could likewise prove fruitful to induce greater R&D investment targeting LMIC challenges for which the gap between enormous societal gains and limited commercial market potential limits financing.

Economies of scale and scope in advanced agricultural biotechnology, combined with IP and regulatory issues naturally lead to competition and anti-trust enforcement issues because patents confer state-sanctioned monopoly power on the IP holder and regulations often create barriers to entry. The past five years have seen unprecedented consolidation among massive global seed and agrichemical corporations, raising important concerns about how industry concentration shapes agricultural R&D investment and TFP growth, a topic about which the evidence base remains exceedingly thin (MacDonald 2019). The worry is that consolidation can discourage innovation, either through catch-and-kill acquisitions of innovative competitors or if there exist internal diseconomies but external economies of scale and/or scope to R&D.

The ongoing geographic mismatch between where agri-food R&D is most needed versus where it is growing, and heightened reliance on scientific methods and data with variable and uncertain regulation, underscore why successful agri-food R&D requires not just investment in new science but policy and institutional change and acts of solidarity with marginalized populations. If we get the right regulatory and market signals in place, adequate R&D financing and breakthrough science will almost surely follow. These sorts of socio-technical bundles will be essential to develop the next generation of improved animal and plant genetic material, chemical, mechanical and digital technologies, and business processes that will make producing healthier, environmentally sustainable foods more remunerative.

De-agrarianization

The prior section made the point that agri-food TFP growth is essential and requires renewed (and changed) investment in R&D. But TFP growth is also insufficient if we are to address the climate, and especially the extinction and pandemic crises. We must move land out of agriculture and into production of environmental and energy services, all while increasing food production so as to drive down real food prices, and especially for healthier foods. This implies a need to de-agrarianize food production, i.e., to decouple from the land, replacing it with capital.[11] While there exist opportunities to expand renewable energy generation with agricultural landscapes, the need to conserve more land for biodiversity will necessitate accelerating the de-agrarianization already underway in HICs.

This change is coming. At least four distinct, rapidly-advancing classes of innovation are poised to facilitate de-agrarianization. The first involves the emergence of livestock feeds based on algae, insects (e.g., black solider fly larvae), etc. as substitutes for land-intensive cereals and oilseeds-based proteins and fishmeal. These novel "circular feed" alternatives currently are costlier than soymeal, maize, hay or fishmeal, but costs are falling rapidly, firms (especially in Europe) are beginning to tap these feed sources, and research increasingly shows that these feeds are scalable, yield ASFs of similar quality and safety as those based on conventional feeds, and potentially offer added health benefits (Caporgno and Mathys 2018; Altmann et al. 2020; Cottrell et al. 2020).

The second are tissue engineering-based methods that culture cells to grow animal tissue outside the body, without the environmental, ethical or financial costs of raising and slaughtering live animals. These "clean" or "cellular" meats have gained considerable attention through start-ups like Memphis Meats and Finless Foods, prompting legislative and regulatory battles over product labeling, i.e., what constitutes "meat." Although these products remain expensive, unit costs are falling fast, in Memphis Meats' case by more than an order of magnitude in just two years (2016-18), and are predicted to fall to the level of conventional ground beef by 2026 (Tubb and Seba 2019).

The third group is controlled environment agriculture (CEA) – so-called "indoor" or "vertical" farming – much of it based on aero-, aqua- or hydro-ponic methods. This is already taking off across urban areas of HICs and Asia, where concentrated demand is booming, especially for year-round production of high-quality, high-value, short cycle horticultural products (WWF 2020). The main disadvantage of CEA is that producers forego free sunshine for

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[11] There may be diminishing returns to capital in substituting for labor, as Vander Doknckt et al. (2020) find overall. But we know little about the returns to replacing land with capital, especially the social returns given the global externalities associated with converting agricultural lands to environmental or energy services.

expensive electricity to stimulate plant photosynthesis. The higher cost of labor in urban markets is also a disadvantage, further encouraging greater capital intensity in CEA than in conventional production methods. Yet commercial outfits such as France-based Nature Urbaine or India-based Kisano are already breaking even or turning a profit. And as electricity costs fall, especially with advances in small-scale renewables (e.g., rooftop solar films and panels), the price competitiveness of CEA improves (Pinstrup-Andersen 2018).

The fourth group of innovations use microbes to produce novel foods through a process broadly known as "precision fermentation." Fermentation is a simple, centuries-old process familiar in all food systems globally. It is used to make beer, cheese, etc. in virtually every LMIC in the world. Recent advances in synthetic biology now enable labs to design micro-organisms, such as bacteria or yeasts, that produce more complex proteins from inexpensive plant-based feedstocks. This is the technology behind, for example, Beyond Meat and Impossible Foods. These firms' rapid growth[12] suggests the commercial viability of at least precision fermentation in the years ahead. Independent assessments confirm that precision fermentation methods, in particular, can scale at costs below those of conventional systems for producing animal-source foods (Buckler and Rooney 2019; Tubb and Seba 2019).

As incomes grow and with them, consumer concerns about nutrition, food safety and the environmental impacts of conventional farm production methods, demand will inevitably grow for each of these deagrarianized methods. Urbanization and rising demand for shorter supply chains will reinforce these patterns. Novel food production methods will inevitably require concerted efforts by AVC companies, educators and policymakers to overcome consumers' natural skepticism about novel products (Siegrist and Hartmann 2020). But this is less true in business-to-business markets supplying food manufacturers and food service providers with ingredients, which individual consumers scarcely notice. These same fermentation-based methods already replaced animal-sourced feedstocks in the production of most human insulin for diabetes treatments and chymosin (rennet) in cheese production, because they quickly came to provide a lower cost, more consistent quality, more scalable product. This seems likely to occur soon in other food ingredient markets (e.g., casein), as advances in the science and engineering continue to boost quality and drive down unit production costs (Tubb and Seba 2019). It is also

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[12] For example, Impossible Foods' products sold in <200 stores in January 2020, but >3,000 as of May (Nierenberg May 22, 2020 WSJ article).

more likely in higher-value final consumer product markets, such as for fish or ground beef. Hence recent, substantial investments in this space by major food companies such as Cargill, JBS, Kraft Heinz, Nestle, PepsiCo, and Tyson, as well as by venture capitalists.

The seeming inevitability of large-scale, low-cost, de-agrarianized food production – along with accelerated agri-food R&D – should cause real food prices to resume the steady downward trend that was interrupted by the rapid run up in real food prices over the 2000-2011 period (Figure 2). This will be good for food security and poverty globally, as well as for the environment. But since the 2010s' run-up in food prices was capitalized into higher farmland valuations, we need to manage that transition carefully, lest it further intensify socioeconomic disruption in rural areas.

Without concerted attention to the sociocultural, policy, and institutional environments that must accompany the rapid technological advances already underway, the coming deagrarianization could unleash creative destruction that could wreak havoc on rural peoples whose livelihoods presently depend on the farm economy. If we simply wait for lower costs of deagrarianized food production to undercut the profitability of livestock and feed crop producers, a trail of farm bankruptcies, farmer suicides, and rural unrest could ensue. Hence the need to move to advance alternative, remunerative uses of rural lands.

One obvious option is renewable energy production. Consumer and business demand for electricity sourced from renewables is growing rapidly and the costs of geothermal, solar and wind energy generation have been falling quickly, especially as smaller-scale production units have become viable. Those smaller-scale units create new revenue-generating opportunities for land owners. Lease royalties from energy firms are growing increasingly remunerative for farmers with well-situated lands. So wind turbines and solar panel arrays increasingly dot agrarian landscapes worldwide.

The risk, of course, is that falling profitability in conventional farming will drive down the opportunity cost of land, enabling the modest number of energy firms to recruit more land at lower rates from the far greater number of landowners. This will be compounded by reinforcing feedback between renewable energy production and novel, non-farm food production methods. Cost-reducing technological change in each sector helps lower costs – and increase profitability and scale – in the other. So, relying just on unregulated energy markets and AVCs seems a high-risk strategy for rural communities.

Carbon markets, supported by carbon taxes and ETS, can help replace agricultural revenues, including on working farms. But this requires far more active, and transnationally coordinated government support for markets to monetize GHG sequestration, which in turn requires lower cost, more reliable digital measurement of GHG fluxes. Establishing reasonable carbon taxes and markets to facilitate socially optimal GHG sequestration patterns has proved difficult in most countries for political economy reasons; wealthy interests stand to pay more to protect the planet (World Bank 2020). Remarkably, big firms – e.g., Cargill, Walmart – are increasingly using extra-market contractual terms to induce farmers to sequester carbon (and improve soil and water quality) through regenerative agriculture, sustainable farming practices, etc. as they seek to build consumer and investor valuation through a partially credence service. And third party service providers to certify compliance with production process standards of various sorts have flourished. Thus far, however, the apparent gains from consumer and business valuation of these services seem to accrue mainly to intermediaries, not to farmers or farm workers (Meemken et al. 2020).

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 that it tracks, transfers to the agricultural sector averaged $708 billion/year 2017-19, of which fully $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. Many economists might therefore argue, with justification, that outright elimination of massive subsidies would be best first. But that seems a political non-starter in most HICs.

So why not transition uncoupled farm payments or expensive market price supports to subsidies for farmer capital investments in renewable energy structures, in land conversion for GHG sequestration, and in the digital technologies – and supporting market infrastructure – necessary to monetize those energy and environmental services? This is already happening at small scale in places like California, Iowa, Massachusetts and Texas. Some US states have created incentives for farms to convert land to wind turbines and/or solar panels, or to add biodigesters to process animal waste. But it could happen at a far larger scale. A more forward-looking approach to the use of politically explosive farm subsidies can safeguard rural communities for the coming future when deagrarianized production methods begin to cut into farm profitability and land values. This can provide essential social protection for rural communities against the coming creative destruction in AVCs.

In some places, large scale public or private non-profit land purchases to conserve lands may be an attractive option. But especially in LMICs, paying private landowners to create protected areas will not often be the best use of scarce fiscal resources, especially if they struggle to enforce conservation rules in protected areas. Carefully calibrated subsidy schemes meant to crowd-in private investment in renewable energy and environmental services provision seems a better general strategy.

Facilitating land conversion from agriculture to renewable energy will also require secure land tenure– including large parts of Africa – where this remains lacking. And it will require concerted efforts to overcome NIMBYism (Not In My BackYard) regarding the siting of wind turbines, solar panels and other nontraditional features on rural landscapes.

These patterns can be replicated in Africa and other LMIC regions, enabling technological leapfrogging as promising technologies that were previously unaffordable – CEA, precision fermentation – are on the cusp of being commercially viable at scale any place with reliable energy, urban access and a marginally scientifically-literate workforce. That covers many countries – e.g., Bangladesh, China, Ethiopia, India, Indonesia, Kenya, Nigeria – where food demand will grow relatively quickly in the coming few decades. LMICs must begin to use rural lands to farm carbon, solar, wind, and geothermal heat, not just crops and livestock. They can simultaneously deploy novel technologies to meet a significant portion of growing food demand from de-agrarianized production processes in urban and peri-urban areas. This can convert agri-food sectors from a GHG source to a sink, shift nutritional transitions towards more nutrient-rich foods, and facilitate a structural transformation that harnesses looming demographic changes to simultaneously boost productivity, sustainability and healthy diets.

Food choice environments and healthy food reformulation

Consumer choice drives market economies. Few consumers choose to consume unprocessed agricultural commodities the way they come off the farm. When not strictly constrained by very low incomes, the vast majority of the diets people consume are processed in ways both rudimentary – e.g., milling grains into flour, slaughtering and butchering animals into meats, pasteurizing milk – and complex – e.g., bakery products, prepared meals, cheeses.

Processors, manufacturers, and food service providers formulate processed foods from agricultural feedstocks. Faced with appropriate market or regulatory signals, they can reformulate those same – and novel – foods.

Product reformulation is widely believed to be among the most cost-effective ways to reduce obesity. Product reformulation is largely voluntary, if often a strategic response to political and social pressures that threaten firms with public regulation or taxes they would rather avoid (Scott et al. 2017). In the absence of such pressure, product reformulation is most commonly pursued to improve taste, shelf life, or convenience – non-nutritive attributes with relatively high income elasticities of demand – or to reduce cost, i.e., to boost profits. With rising incomes, market incentives have too often led to processed foods becoming more unhealthy over time. For example, market incentives have naturally led processors and manufacturers to mill away most of the fiber and nutrients in cereal grains. This directly leads to the assessment that insufficient intake of whole grains is a leading cause of disease globally (GBD 2019). It likewise induces AVC firms to add salt, unhealthy fats, sugar, and potentially carcinogenic preservatives to prepared foods, leading to other diet-related diseases (GBD 2019).

This trend can be reversed as consumers increasingly value foods' other non-nutritive attributes, especially credence attributes associated with the product's healthfulness, environmental footprint (e.g., as reflected in Rainforest Alliance certification) or social justice origins (e.g., Fair Trade labelling). The rise of credence valuation of foods also boosts incentives to reformulate in pro-social directions. Producing food with more environmentally and/or socially desirable attributes must be incentivized adequately, either through regulatory or stakeholder-imposed constraints, or through market rewards. Few executives of publicly traded AVC firms can trade away profit and keep their jobs.

Reformulated foods are a complement to increased consumption of fresh, whole foods. There are, of course, limits to the role of product reformulation, and reformulation can work against consumption of fresh, whole foods by normalizing ultra-processed foods (Scrinis and Monteiro 2018). But because most food value addition occurs post-farmgate, we must pay attention to what happens downstream from commodity producers. This requires food science R&D but also social and policy tweaks, another set of socio-technical bundles. Conventional economic factors – e.g., incomes, prices –exert the largest effects on dietary behaviors. But it is increasingly clear that many subtle features of consumers' "food choice environment" also exert considerable influence, perhaps especially among food insecure populations (Just and Gabrielyan 2016). These choice environment features are often changeable.

Labeling is the most familiar approach to try to change consumers' choice environment by putting information in front of them in an express attempt to influence purchasing behaviors. In so far as campaigns to nudge consumer behavior via front-of-label messages and taxes has an effect, it should also induce food processors and manufacturers to reformulate products to follow shifting demand. There is some evidence of this happening, but the magnitude of such effects generally seems rather small (Kiesel et al. 2011; Long et al. 2015; Morrison et al. 2019; Meemken et al. 2020; Cadario and Chandon 2020; Temple 2020), and much remains to be learned about how policy can affect food choice environments at scale (Schwartz et al. 2017).

A more brute force method is to impose Pigouvian taxes (subsidies) on unhealthy (especially healthy) foods – or on foods with demonstrably adverse environmental impacts – in an attempt to internalize public health and environmental externalities (Allcott et al. 2019). But one needs to be careful about food taxes, for multiple reasons (Just and Gabrielyan 2016). First, they tend to be distributionally regressive, especially when imposed on low priced foods favored by more price-sensitive low-income consumers. Second, taxes that are too specific – e.g., just to specific classes of sugar-sweetened beverages, or only within a city's limited jurisdiction – are easily avoided through product or spatial substitution effects, thereby diluting the behavioral impacts. Third, tax and subsidy policy is a precarious political economy path to follow, easily subject to interest group capture. Pigouvian taxes and subsidies are useful tools, because the externalities of in agri-food systems are too big to ignore, but are perhaps best deployed judiciously and modestly.

Hence the importance of institutional and sociocultural changes that seize on consumers' relatively high income elasticity of demand for credence attributes and the fact that such attributes reduce consumer price responsiveness. Social influencers – especially those who influence cooks and young people forming their dietary habits, such as celebrity chefs, athletes and entertainers – can more often popularize and promote healthier foods and discourage eating or preparing foods heavy in fats, salt and sugar. The rapid increase in social acceptance of plant-based foods over the past few years has been remarkable. It wasn't long ago that restaurants would, at best, make vegetarian offerings quietly available on menus to the hard core who asked for them. Today, major fast food chains mount mass advertising campaigns for foods based on plant-based proteins. And it’s working, as illustrated by Impossible Foods’ phenomenal growth in retail penetration during the 2020 pandemic. Shifting norms is a powerful force influencing cooking and eating behaviors, which ultimately drive AVC firms’ strategic behaviors.

Digital technologies to build trust and cooperation and de-risk

Digital technologies have been transforming agri-food systems for a generation. The rise of precision agriculture through GPS-enabled machinery, computerized dairy parlors, web- and SMS-based extension services delivery, and electronic trading platforms have transformed farm management and marketing. Meanwhile, robots, sensors, and artificial intelligence (AI)-driven logistics and marketing have reshaped post-harvest AVCs. And social protection programs have moved increasingly to electronic transfer systems to reduce costs, delays and fraud in benefits delivery.

Digital advances will become more important still in the years ahead as information becomes even more valuable in managing growing risks, in reducing transactions costs and thereby resolving input and output market failures in Africa, in customizing actions and products to meet heterogeneous needs throughout AVCs, in facilitating GHG management, and in resolving information asymmetries so as to unlock credence valuation of food attributes. High-speed access to digital information through wireless communications, cloud computing, and AI, connected via the internet of things (IOT) through drones, computerized machinery, robots in fields, factories and vehicles, will continue to transform AVCs at a rapid rate. This will likely prove especially transformative in rapidly urbanizing middle-income economies, enabling technology leapfrogging to bypass older production and exchange methods. But in the digital space too, socio-technical bundles will be essential to unlock the potential of the computer and information science and engineering by addressing challenges concerning equity, privacy, data ownership, misinformation, and industrial concentration.

Five areas of advance merit special note. First, digital technologies play an increasingly important role in reducing the uninsured risk exposure of agri-food systems agents. Internet-connected sensors in drones, farm machinery, robots, satellites – soon, even within plants and animals – enable earlier and more reliable detection and treatment of crop and livestock diseases, heat or water stress, soil mineral toxicity or nutrient deficiencies, etc., thereby facilitating reduction of the risk of adverse shocks and the magnitude of those shocks that cannot be avoided. Robots offer insurance against labor supply disruptions, as have occurred during the COVID-19 pandemic (Christiaensen et al. 2021). Digital methods not only improve risk reduction they can also enhance risk transfer through improved spatial arbitrage (Jensen 2007; Aker and Mbiti 2010), and agricultural index insurance products designed off satellite-based remote sensing data streams (Chantarat et al. 2013).

Second, digital technologies can facilitate TFP catch-up in low-income regions where food demand will grow fastest – e.g., SSA – not only by introducing improved production and exchange methods but also in helping resolve widespread factor and product market failures (Dillon and Barrett 2017) that lead to significant allocative inefficiencies. Enhanced digital connectivity, through apps like Hello Tractor in several SSA countries, can especially help activate factor market failures to overcome the lumpiness of capital investments in machinery dramatically broadening access to productivity-boosting machinery, as occurred in Vietnam (Liu et al. 2020). Digital technologies as simple as basic SMS or USSD mobile phones have demonstrably big impacts in reducing transactions costs and resulting price dispersion (and volatility), as well as in enhancing inter-firm competition that reduces quality-adjusted consumer prices (Jensen 2007; Aker and Mbiti 2010; Jensen and Miller 2018). Digital technologies also enable the rise and expanded reach of commodity exchanges that can help resolve price discovery and risk management challenges facing rural AVC actors.

Third, digital technologies will be essential to de-agrarianization. It is hard to imagine viable, scalable carbon markets emerging to help induce land conversion from agriculture into environmental services without improved sensor technologies to provide reliable, near-real-time estimates of carbon sequestration in soils and vegetation. Robots can also help address the higher urban and peri-urban labor costs while digitally controlled environments can help optimize the cost-effectiveness of indoor growing conditions, both enabling growth of non-farm food production.

Fourth, digital technologies can resolve information asymmetries, thereby boosting consumer willingness to pay for credence attributes, rendering viable AVC business models – including direct-to-consumer marketing – that can internalize what are presently externalities and thus do more than merely greenwash sustainability and social justice concerns. It can only work, however, with digital sensors and secure traceability that build trust through reliable verification methods. Such methods can also help advance food safety and enable precision nutrition and customized food reformulation to address allergenicity, metabolic and other diet-related health challenges. Opportunities abound for AVC intermediaries that can cost-effectively and reliably integrate data from both suppliers and consumers so as to adjust production processes to create higher-value foods.

Fifth, the ongoing digital revolution can also improve food assistance program performance. Near-real-time remotely-sensed or crowd-sourced data can be analyzed to generate increasingly reliable indicators of food supply conditions (Lobell et al. 2020, Porciello et al. 2020) and needs assessments (Jean et al. 2016; Fanzo et al. 2020, Yeh et al. 2020), thereby enhancing early warning and targeting systems. Those programs will rely increasingly on low-cost, secure transmission of mobile cash and vouchers – especially in conflict-affected areas where delivery is costly and dangerous and rapid response to SAM is of greatest humanitarian importance.

None of these exciting technologies can achieve much without addressing broader policy and institutional issues. Equity of access is perhaps the most obvious, as massive digital deserts exist in poorer communities throughout the world. Subsidized universal broadband service will be especially important in low-income rural areas, much like subsidized communications, postal or transport services have been to date. Universal internet access will, in turn, require expanded access to electricity, especially in Africa where less than half of households have access and population growth has outpaced electrification in recent decades (Blimpo and Cosgrove-Davies 2019).

The IP and market power issues that influence technological change more broadly loom especially large in the digital space. Data interoperability and service bundling opportunities enable considerable economies of scale and scope – and network externalities – that can concentrate market power in the absence of adequate protections for small farmers, small-and-medium sized AVC businesses, consumers, and data owners. Open source IP and digital data commons may prove especially important in places like Africa and Asia where the rules of the game are less well defined currently (Porciello et al. 2020). Questions of privacy and data ownership also loom large, as does regulation of misinformation, which seems to diffuse faster, farther, and deeper than truth (Vosoughi et al. 2018).

Rethink policies and institutions to promote group fitness

Perhaps the biggest challenge will be to rethink the fundamentals of the institutions that underpin economic life. As the Nobel Laureate Elinor Ostrom (2009, p.435) emphasized in the closing passages of her Nobel lecture,

> "humans have a more complex motivational structure and more capability to solve social dilemmas than posited in earlier rational-choice theory. Designing institutions to force (or nudge) entirely self-interested individuals to achieve better outcomes has been the major goal posited by policy analysts for governments to accomplish for much of the past half century. Extensive empirical research leads me to argue that instead, a core goal of public policy should be to facilitate the development of institutions that bring out the best in humans."

The big challenges we face in achieving global food security, while necessarily addressing climate, extinction and pandemic crises, require cooperation and trust. Policies are too often designed to promote optimal individual behavior, taking into account any resulting externalities. Weiner's (2019) powerful observation about plant science mirrors Ostrom's point. Weiner argues that plant scientists may be looking in the wrong direction for higher-yielding crop genotypes by trying to boost individual fitness, rather than population-scale performance. Social scientists may be committing the same error. By reducing analysis to microfoundations, we may inadvertently focus attention excessively on individual outcomes and too little on group fitness.

Some serious re-thinking is needed about how best to tailor local, national, and global institutions and policies to promote greater cooperation, more trust, and increased altruism, not just to constrain bad behaviors and promote healthful competition. Altruism, cooperation and trust are as much natural human instincts as is self-interest (Ostrom 2009; Nourani et al. 2020). Indeed, trust gaps may hold back economic performance as much as do "object gaps" (i.e., insufficient capital investment) and "idea gaps" (i.e., inadequate R&D and facilitation of discovery), particularly in nations where intense commercial and political competition, weak enforcement of laws and regulations, and growing misinformation have undermined trust (Arrow 1974; Barrett 1997). Especially as foods' credence attributes and global public goods concerning climate and infectious disease grow in importance, we must find new and better ways to promote trust and cooperation. Elementary game theory teaches us that cooperative outcomes always Pareto dominate non-cooperative outcomes. Future global food security – and many other desirable goals – depend on finding new institutional means to advance cooperation and trust.

This goal, like everything else I have discussed in this essay, fundamentally turns on combining science with solidarity. We must be progressive in both senses of the term, having faith in science as an engine of societal advance, and standing with marginalized populations. The twinning of science and solidarity reveals the importance of socio-technical bundles, not just technological advances on their own. Socio-technical bundles have succeeded before in delivering us from harrowing food security crises. They can do so again if we direct human ingenuity towards tomorrow's challenges rather than yesterday's.

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