CHAPTER 12

The Future of Food: Meeting Human Needs with Systemic Change

12.1 Agribusiness and Agroecology: The Environment, Climate and Resources

12.1.1 Motivation and Guiding Questions

We start this chapter with agricultural production and food supplies. How can farms, fisheries and livestock systems adapt to meet growing needs on a rapidly changing planet? What can consumers, institutional decision-makers or government policies and programs do to facilitate resilience and help producers thrive in new environments?

Each farmer has a powerful incentive to be a careful steward of their own resources, such as the soil quality and moisture level of their own fields. They also have high stakes in collectively owned resources such as underground aquifers, but some effects of what they do are far away such as fertilizer runoff that causes downstream algae growth, or methane emissions than cause climate change. Agriculture both contributes to and is harmed by environmental change, playing a central role in the new green revolution towards decarbonization and resilience.

In this section we introduce the economics of innovation, including the role of public and private research and development, and farmer decisions about whether to adopt new methods. Innovations often involve new inputs that substitute for natural resources, using knowledge and capital to produce more with less.

By the end of this section, you will be able to:

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1. Define and describe the principle of induced innovation for new technologies, policies and institutional arrangements in agriculture and other enterprises;
2. Use available data to describe intensification of input use, using the examples of total fertilizer use and yield of cereal grains around the world;
3. Use available data to describe changing use of natural resources, using the examples of cropland for cereals production and transition from wild-caught fish to aquaculture;
4. Describe how agriculture and food enterprises might change to meet food demand in ways that address climate change, demographic trends and societal needs around the world.

12.1.2 Analytical Tools

Agriculture and food play a leading role in humanity's relationship to the natural world, including longstanding concerns about land and water, and the urgent new priorities of mitigation, adaptation and resilience to climate change. Mitigation helps reduce future harms, adaptation responds to harms that are already occurring and resilience is the ability to recover and thrive despite setbacks.

Food production methods are among the most varied and diverse kinds of human activity, and can change rapidly when new opportunities arise. Variation and innovation in agriculture has been a distinctive strength of our species for over ten thousand years, enabling populations to survive and grow in every ecosystem on the planet. The pace of innovation has accelerated over time, as discoveries and technological developments in other domains provide new ways to improve agriculture itself.

One of the most important inputs to innovation is knowledge about what people are likely to need in the future, anticipating trends so that methods are adapted to future conditions. The principle of *induced innovation* says that new inventions can and should use resources that are increasingly abundant, and substitute away from resources that are increasingly scarce. In so doing, agricultural change advances through continuous interactions between people and the planet, altering the work of agriculture-related businesses in response to and in anticipation of changes in natural resources and agroecological conditions. What farmers do is influenced by government policies and programs as well as farmer organizations and civil society, but a convenient shorthand for how innovations scale up to reach all farm enterprises is *agribusiness*. Similarly, the environmental conditions under which farmers work involve many aspects of soils and water, climate and biodiversity, but a convenient shorthand for understanding the natural resources around farm enterprises is *agroecology*. The future of food depends on innovations in both domains, for agribusiness to work with agroecology in ways that meet each person's need for a healthy diet, decent work and resilience to shocks.

Induced Innovation, Agribusiness and Agroecology

Induced innovation applies to every scale of technical change. Most broadly, for most of the nineteenth and twentieth centuries, the increasingly abundant resource driving innovation was fossil fuels. Coal, oil and gas replaced the use of animals for power, and also replaced human labor, waterwheels and windmills. The direction of change turned in the 1970s, and induced innovation turned decisively towards electrification from renewable fuels with the rapidly declining cost of solar, wind, batteries and other means of decarbonization.

Within agriculture, the most fundamental change in resource scarcity driving innovation is population growth and land availability. When and where the labor-to-land ratio is rising, farmers need to intensify crop and livestock production for higher yields per acre. At other times and places, the labor-to-land ratio may be falling, so farmers are looking for ways to use more acres through livestock and mechanization. Induced innovation also applies to the mix of crops and foods produced. When the low-income population of the world is growing, the highest priority is to meet dietary energy needs with low-cost starchy staples and vegetable oils. As incomes rose priorities shifted towards more expensive foods including animal products, processed and packaged items and now with greater longevity priorities can shift towards foods for health.

The term agribusiness is most often used for companies that sell inputs and commercial services to farmers, while agroecology refers to how food is or can be produced using ecological principles and ecosystem services. Initiatives favoring agroecology typically advocate for less use of all industrially produced inputs, with food outputs sustained by closing the loop of nutrient cycling between plants, animals and the soil that sustains them. Initiatives favoring agribusiness typically favor more use of industrially produced inputs, despite runoff loss of nutrients and emissions that change the climate.

Global agriculture includes all kinds of farming. At one extreme, small farms using permaculture and similar techniques aim for closed-loop systems with no industrially produced inputs at all. The other extreme includes cattle operations in Brazil involved in illegal deforestation of the Amazon that are among the world's most environmentally harmful production systems. Most agriculture in each region evolves between those two extremes, using more or less agroecological principles with more or less inputs from agribusiness. Like the problem of dietary transition from inadequacy to excess and then just-right nutrition, agricultural production can and must avoid doing too little or too much of each thing, for a just-right balance of inputs to sustainable productivity growth.

Production Methods, Input Use and Intensification Within Resource Constraints

Many kinds of innovation and new investments will be needed for agriculture to meet humanity's need for healthier foods, produced in more inclusive and sustainable ways. To illustrate the range of innovations, a few examples that are used on many different crops and farms of all size include laser leveling, terracing or micro-catchments and reduced tillage for soil and water conservation; application of soil micronutrients like zinc, iron and boron to remedy deficiencies and improve crop yield and nutritional value; seed treatment and inoculation to improve germination and growth; and precision application of water and nutrients or plant protection techniques to reduce energy use, waste and runoff. Different kinds of innovation often complement each other, as alleviating one constraint on plant growth and farm operations makes alleviating the next constraint more valuable.

Which agricultural innovations are needed for each food product is specific to each place and time, but generally starts with selective breeding to alter the genetic potential of each species. Throughout history farmers have hand-selected their seeds and bred their own animals, producing crop varieties known as landraces that were well-suited to farmers' needs in the distant past. The development of randomized trials and statistical hypothesis testing in the early twentieth century occurred in large part to improve crop breeding, and was accompanied by systematic collection and cataloging of landraces from around the world to identify desirable traits from a wider range of backgrounds, improved techniques for crossing and selection from the full range of genetic potential and new methods for seed multiplication and distribution to farmers.

Throughout the twentieth century, crop breeders around the world worked in public and private institutions to improve dozens of commercially important species, creating many thousands of unique varieties suited to different purposes in each location. Tailoring the plant's genetic potential to local conditions improved its responsiveness to farm management and input use, making it worthwhile for farmers to invest in soil amendments, moisture control and plant protection against pests and weeds. Those investments to improve growing conditions set the stage for a next round of genetic improvement, again raising yield potential and responsiveness to additional nutrients, water and plant protection, potentially up to the ultimate yield ceiling for each species dictated by the total energy in sunlight.

As each round of innovation proceeds in any farming system, pathogens evolve to exploit the new agroecosystem. Pathogens would evolve even without agricultural innovation, but changing conditions creates new opportunities for all kinds of pests and weeds. Resistance to each pathogen is sometimes found from the existing catalog of genetic material collected from all around the world, and sometimes found using existing or new biochemical techniques for plant protection. New varieties and agronomic techniques are also needed to address changes in climate, water availability and other factors.

Productivity growth in crop production comes from the speed and accuracy with which new crop varieties and the accompanying management techniques can be tailored to changing agronomic conditions, and delivered to farmers on time and at scale in ways that are profitable for farmers to adopt. In settings with rapid increases in farm productivity, each new crop variety might be planted for just a few years before it is replaced by a better variety, and each successive new variety might be more narrowly tailored to a specific location, so the number of varieties in current use will grow over time. For some crops like corn and soybeans in the mid-western U.S., the plants' above-ground appearance is uniform but the genetic material underneath varies from in response to small differences in the environment, and varieties are quickly replaced over time.

From the entire universe of selective breeding and agronomic improvement over the twentieth century, a handful of species with breakthrough innovations emerged as the principal success stories. One fundamental step was to make the stalks of wheat and other crops shorter than the landraces selected by farmers. Landraces are often tall in part to shade out competing plants and weeds, but when planted simultaneously with sufficient weed control a short plant can concentrate energy in the grain. Another breakthrough was to make the leaves of corn plants stand up instead of spreading out, and then plant seeds closer together. Landrace varieties of corn were selected in part for yield per seed planted, whereas modern seeds produce less grain on each plant and are planted with many more seeds per field. These and other changes made other innovations more attractive, so that crop breeders could select for other traits such as pest resistance, efficiency in use of moisture and soil nutrients, and nutritional composition of the grain, and yield stability as well as average yield and for many other aspects of plant growth.

The steps needed for a flow of improved varieties and accompanying agronomic inputs to increase farm productivity start with a population of self-motivated family farmers who know their own needs better than anyone else, and a set of researchers in regional or national organizations able to conduct randomized trials and generate a flow of innovations tailored to those needs. The two are connected by education and extension to spread information and other public goods and services, and competitive rural markets or farmer-owned cooperatives through which farmers can buy and sell the products they need. Success stories can occur under almost any set of climatic and agronomic conditions, but the payoffs to innovation are greater where natural resources and infrastructure are more favorable. Innovation systems involve public goods dependent on government support, and therefore arise primarily in countries where governments have an interest and commitment to helping farmers grow more food.

Once farmers start increasing the yield harvested from a field they must replace the lost nutrients. Improved genetic potential, soil moisture management, plant protection and additional nutrients are all jointly needed for yield growth, but applying more nutrients typically follows rather than leads the sequence of innovations. One reason is that most crop improvement happens in places that were favorable to plant growth in the past, so their soils have a reservoir of nutrients that can be drawn down and then replaced with fertilizer. Two other reasons are that plant genetics selected in the past were not chosen to have higher yields when more fertilizer is applied, and nutrients are expensive while new seeds can be multiplied at low cost. Adding nutrients before genetic improvement therefore tends to have low returns and high costs, while new seed varieties can be adopted with fertilizer application rates that grow with the yields actually achieved.

Many different aspects of agricultural production are important for the future of food, but an especially useful starting point is the degree of intensification in soil nutrient use shown in Fig. 12.1.

The data on total fertilizer use per hectare in Fig. 12.1 are shown on a log scale, so that a straight line would be a constant percentage rate of growth. The horizontal guidelines from 1 to 10 kg/ha are in increments of one, the guidelines from 10 to 100 are in increments of ten and the guidelines above 100 are in increments of one hundred. Only selected regions are shown, but the data show clear patterns of change and difference between regions.

Starting at the top, the 27 countries forming today's European Union (EU) used around 100 kg/ha in 1960, far higher than North America at around 38 kg/ha. South Asia began with the lowest rate of fertilizer use but grew quickly to pass the world average in the 2000s, and a level above that of the EU and North America, partly because EU fertilizer use dropped back to levels observed in the 1960s. Africa's fertilizer use grew after independence in the 1960s and 1970s but stopped increasing in 1980 at a time of financial crisis, and fertilizer use growth did not resume until after 2005. One factor in

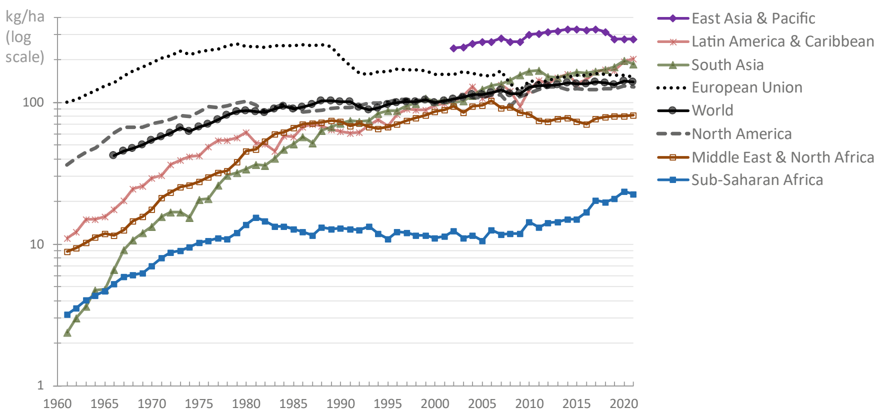

Fig. 12.1 Crop intensification as measured by fertilizer use, 1961–2021 *Source*: Authors' chart showing total nutrients, in kilograms per hectare of arable land, using FAO data as reported by the World Bank, World Development Indicators. Includes only major nutrients [nitrogenous fertilizers for N, potash for K, and phosphate for P, including ground phosphate rock], omitting other soil amendments [animal manure, plant residues and mulch or compost, lime for pH, zinc and other nutrients]. North America is the U.S., Canada and Bermuda. Other countries and regions and updated data are at https://databank.worldbank.org/Fert.-Use-and-Cereal-Yield/id/38545265

that trajectory is that the initial growth in Africa's fertilizer use was not done with limited rollout of new varieties and little pressure for intensification from population growth. In contrast, fertilizer use after 2005 occurred once new varieties had become more widely available, and rural population density was high and rising.

Fertilizer use is a very crude measure of intensification, and relates to productivity growth through a variety of other factors such as soil moisture, infrastructure and markets that determine which crops are grown. For the most basic and longstanding aspects of food production, a useful starting point is cereal grain yields per hectare. Different cereals have somewhat different price and nutritional value, and yield per hectare is driven by many different factors that influence production, but adding up total cereals produced per hectare of land used for cereals provides a simple and informative indicator of productivity.

Results for selected regions of the world are shown in Fig. 12.2.

Cereal grain yields are just one part of the world's agricultural production growth story, but the variability and trends shown in Fig. 12.2 are very revealing about the future of food. Again the vertical chart is in log terms so a straight line is a constant annual percentage rate of growth. Starting at the top left, North America had a slightly less growth and more variability in yields than the EU countries from 1961 through the 1980s, but EU yield growth

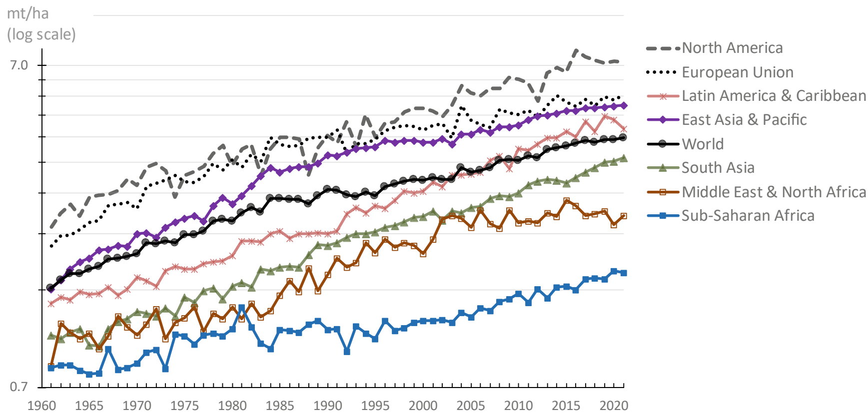

Fig. 12.2 Crop productivity as measured by average cereal yields, 1961–2021 *Source*: Authors' chart showing total yield, in metric tons per hectare harvested, using FAO data as reported by the World Bank, World Development Indicators. Cereals include wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains that are harvested for dry grain only, excluding crops harvested for hay, feed, or silage, used for grazing, or harvested green as fresh corn. Years refer to harvest, not utilization which may occur in the following year. Countries and other regions can be obtained with updated data at https://databank.worldbank.org/Fert.-Use-and-Cereal-Yield/id/38545265

slowed after 1990 while American yields have continued to rise at about the same annual rate to 2021. This reflects the very different circumstances of the two agricultural systems, as the EU's much higher initial level of fertilizer use and greater population density made further yield growth a low priority. Since the 1990s, European decision-makers have pursued other objectives, moving away from increased yield towards other ways to help farmers and improve rural environments.

East Asia and the Pacific had about the same cereal yields as the global average in 1961, then raised yields much faster than other regions until the early 1980s, after which their yield growth slowed when they too pursued other priorities. The Latin America and Caribbean region had the opposite trajectory, with their cereal yield growth rates below the world average from the 1960s through the 1980s, after which their yield growth accelerated to above the world average.

South Asia had about the same average yield level and growth as the Middle East and North Africa through the 1960s and early 1970s, but continued to raise yields at a roughly constant percentage rate to approach the world average, and also improved yield stability. Cereal yields in Sub-Saharan Africa grew but were highly variable in the 1960s and 1970s, then had no further growth until the 1990s. Prior to the African countries' independence in the 1960s, colonial governments had focused public-sector efforts on the export crops from which they derived tax revenue, and relied on land abundance for food supplies. Africa continued to have the world's most land-abundant agricultural systems through the 1970s, making yield per acre a low priority for national governments until the 1990s.

Sub-Saharan Africa's cereal yields since 1990 have grown roughly in parallel to South Asia, but at a much lower level. Since the 1990s, many African farmers and food consumers have benefited from the gradual rollout of new seed varieties and plant protection methods, accompanied by the increased fertilizer use per hectare shown in the previous chart, but by far the most important driver of yield growth has been increased labor use. That labor has been used to plant new fields which had been previously used for grazing and in some cases forestry, and to plant each field more often. Historically, many farming systems had so much land abundance that farmers would leave each field fallow for several years, building up soil nutrients from spontaneous growth of plants that they burned or cut before plowing and planting. Farmers in other regions had been forced into continuous cropping many decades earlier, using crop rotation and intercropping as well as manure and crop residue management to maintain fertility, and African farmers adopted those methods as well when their labor-to-land ratios rose in the 1980s.

Each region shown in these charts has great internal variation among and within countries, including differences in the accuracy of yield estimates. Each farmer's need and ability to measure their own crop yields, and each government's interest in building an agricultural statistics service capable of accurately estimating the country's total area and quantities harvested, is itself an important part of induced innovation in agriculture. For most of human history, the scarce input to cereals production was the seed. Putting grain into the ground instead of eating it was a painful decision, and yields were measured as the weight of grain obtained per seed planted. Even today, despite the scarcity of land and water, farmers have no need to accurately measure the area of each plot until it is profitable for them to apply expensive inputs like fertilizer in the precise quantities needed. Surveys show that farmers who are just starting to use purchased fertilizer make small but significant errors in measuring their own fields and choosing application rates, making it worthwhile to invest in more precise measurement.

Variation within regions and differences in the accuracy of measurement are important, but it is implausible for the total cereals production, area and average yield of entire regions to have been under- or over-estimated systematically in ways that changed enough to alter the trends shown in these charts. In fact the totals and averages for entire regions over many decades are important precisely because of the variation and measurement error affecting each location.

To help us understand the past and anticipate future changes, the shifting allocation of land to or from cereals, including the use of land that had been fallow or pasture and forestry in Africa as well as shifts in cropland allocation between cereals and other crops, is shown in the area data in Fig. 12.3.

The data shown in Fig. 12.3 are in millions of hectares, with guidelines in increments of 20 million hectares. Sub-Saharan Africa had some area expansion

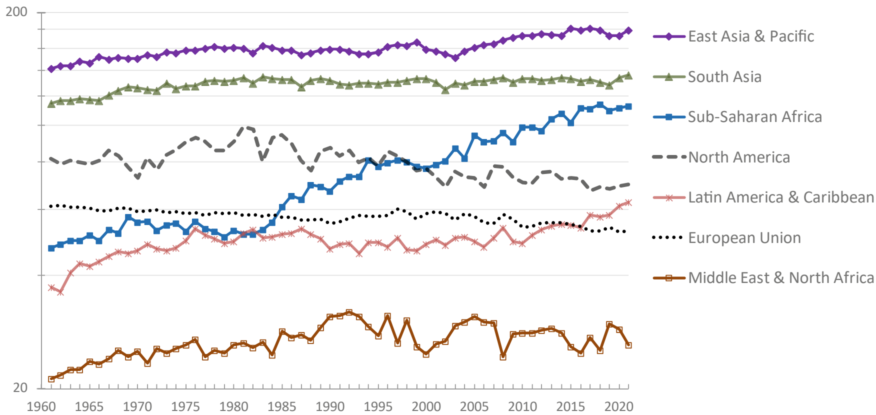

Fig. 12.3 Area used for cereal grains in selected world regions, 1961–2021 *Source*: Authors' chart of total area, in millions of hectares [log scale], using FAO data as reported by the World Bank, World Development Indicators. Land under cereal production refers to harvested area, although some countries report only sown or cultivated area. Countries and other regions can be obtained with updated data at https://databank.worldbank.org/Fert.-Use-and-Cereal-Yield/id/38545265

immediately after independence in the 1960s, then none until the mid-1980s, and is the only major region with large-scale expansion of cereals area since then. The total area of cereals in Africa is now close to that of South Asia, which had expanded in the 1960s and early 1970s but not since then. Cereals area in the North America has declined since 1980, and has declined in Europe since the 1960s.

The future of food will not be like the past. As shown by the trajectories of fertilizer use, cereals yield and cereals area in these charts, each region's agricultural technologies and land use changes with the changing priorities of farmers and national governments. When governments respond, and farmers are able to adopt valuable innovations, productivity per worker and per unit of natural resources can grow quickly.

Data about other crops and livestock systems could be used to chart trajectories similar to those shown for cereals, adding up to the changes in availability by food group that was shown in Section 10.2 on food system transformation. Cereals are important mainly because of their magnitude and comparability around the world.

To illustrate the magnitude of agricultural intensification and transition from natural resources to investment in innovations, another useful global picture to understand the future of food is the fisheries transition shown in Fig. 12.4.

As with cereal grains, the fish production estimates shown in Fig. 12.4 are the sum of national reports compiled by the FAO. Each country's data

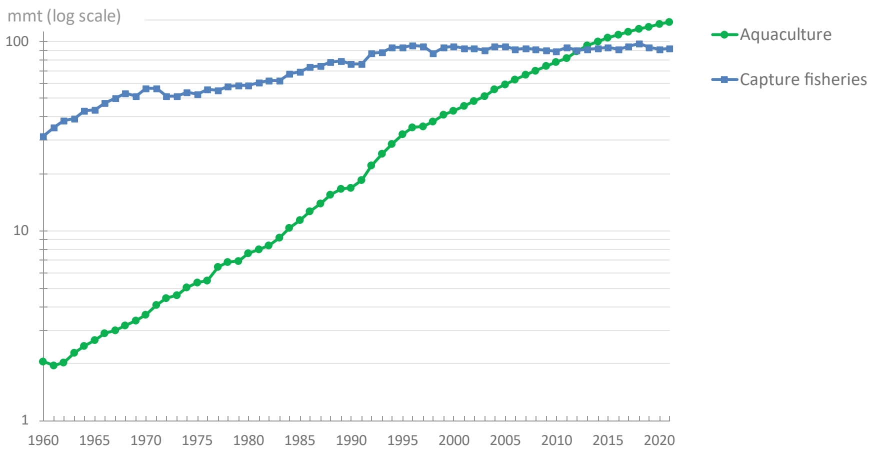

Fig. 12.4 The global transition from capture fisheries to aquaculture, 1960–2021 *Source*: Authors' chart showing total worldwide production, in millions of metric tons, using FAO data from the World Bank, World Development Indicators. Other regions, countries and updates are at https://databank.worldbank.org/From-Wild-Caught-Fish-to-Aquaculture/id/b567055f

are subject to measurement error, especially for the volume of captured fish which is systematically underestimated when international fleets violate catch limits. The data show rapid growth in wild-caught fish in the 1960s, slightly slower growth in the 1970s and 1980s, and no further growth in measured catch since then. Multiple factors contributed to that change, including overfishing that reduced the potential catch and hence profitability, but if that were the only story then volumes caught would have fallen. Instead, international treaties were used to establish 200-mile exclusive economic zones (EEZs) within which national governments could establish catch limits, and thereby slow down what remains the world's largest wild-animal hunt.

Even before government regulations slowed and perhaps ended growth in the pursuit and capture of wild fish, the world had exponential growth of aquaculture. That growth rate was roughly constant from 1960 through the 1980s, accelerated briefly in the 1990s, and has grown more slowly in recent years. The FAO's rough estimate of when the world reached half of its fish from cultivated sources is 2012.

The data shown in this section are totals per year, not per capita, to illustrate how food systems have shifted from more extensive using up of the world's natural resource to more intensive cultivation, through investment in innovations such as aquaculture. The techniques used for intensification are varied and complex, employing thousands of scientists in hundreds of public-sector institutions and private enterprises to identify opportunities, develop new methods and deploy them at scale among commercial food producers around the world. Experimentation generates countless new ideas, only some of which are sufficiently promising to attract investment for commercial delivery, and only some of those turn out to be sufficiently successful for widespread adoption.

Selected Examples of New Frontiers in Global Agriculture

Innovation in agriculture is not any one thing. Different growers need different things at each place and time, and all producers need a sequence of innovations to overcome the new problems that arise when previous problems are resolved. Individual farmers and private enterprises are constantly experimenting with alternative approaches to their work, drawing on public domain knowledge and other resources to adapt and adopt whatever methods and inputs turn out to work best under their circumstances. Studies have revealed some differences among people and enterprises in their degree of inventiveness and openness to new ideas, some of which are associated with long-lasting cultural and institutional differences, but surveys consistently reveal that new agricultural production methods are adopted to the extent that they actually meet farmers' needs. New techniques that work elsewhere or seem attractive from a distance often turn out to be poorly suited to local conditions, and even if an innovation works it may take a few harvests for the news to spread, but farmers who rely on agriculture for their livelihood have consistently been found to adopt whatever new inputs and production methods work best for them.

Because farmers and private enterprises are constantly experimenting with factors that are within their control, the driving force in the speed of innovation is whether government and philanthropic institutions provide a sufficient flow of new public goods and services tailored to evolving agricultural conditions. The future of food relies on farmers and other enterprises adapting and adopting those ideas, but history shows they have consistently done so. The variation we observe comes mostly from differences in government policies, such as the changes shown in this section for cereal grains and aquatic foods. To illustrate the variety of innovations needed in global agriculture, this section closes with just a few examples below.

Anti-spoilage Technology and Food Safety

Food preservation techniques are needed to protect against contaminants and pathogens for food safety, maintain or enhance nutritional values for health and limit the extent of food loss and waste. Ancient techniques include fermentation of grains and other starchy staples as well as dairy products and some vegetables such as cabbage for kimchi; drying and smoking especially for fish and meat or dehydration of fruit; and milling cereal grains to remove the oil and limit rancidity from oxidation. Techniques developed during the industrial revolution centered on canning, freezing and refrigeration, and the development of chemical preservatives. In the late twentieth century, innovation focused on anaerobic handling and packaging, including the use of nitrogen or other gases to protect foods from oxygen, or simply keeping a hermetically sealed bag or container closed so that additional oxygen cannot enter.

One modern frontier in food preservation of special interest for diet quality and nutrition is the use of edible films on the surface of produce. Moisture is locked inside the fruit or vegetable, and oxygen is prevented from entering. Edible films could potentially make fruits and vegetables more attractive to consumers than current forms of packaging and sale, and offer a new form of value added that helps reduce diet-related disease.

As in other fields, the success or failure of food safety innovations often depends on the incentives created by regulation, such as the U.S. Food Safety Modernization Act of 2011 and its gradual implementation by the Food and Drug Administration (FDA). The FDA was established through the Pure Food and Drugs Act of 1906, making it the world's first national agency with broad powers to regulate many kinds of food, but changes in the sector and limited funding for enforcement continue to attract interest in how best to limit foodborne illness. The need for further reform was highlighted by persistent infant formula shortages in 2021–2022 caused by bacterial contamination at poorly inspected manufacturing plants. In the U.S., food safety concerns from animal source foods are regulated by the USDA, and some issues such as antimicrobial resistance due to prophylactic antibiotic use in livestock or the improper use of pesticides are regulated by multiple agencies with overlapping jurisdictions.

Precision Agriculture and Information Technology

Precision agriculture is an umbrella term for adjusting the rate and timing of input use within each field, in contrast to uniform application over the entire plot. Variable-rate application typically reduces the total quantity of each input used, because prior methods had blanketed each field leading to more runoff, leaching and evaporation than when precision methods are used. Some precision application can be done by hand in very labor-intensive farming systems, but most relies on the combination of GPS positioning for farm equipment, optical and chemical or other sensors to map soil and plant conditions then measure the harvest from each location, and variable-rate applicators for water, fertilizer and chemicals for plant protection. Most of this is surface equipment, but airborne drones also play an increasing role, and some satellite imagery or other remote sensing and weather mapping is also involved.

A central challenge for precision farming, like any information technology, is what to do with the information. When GPS devices and variable-rate technology was first put on U.S. farm equipment in the 1990s, its most popular initial use was to steer the tractor more precisely. This reduced the degree of skipped or overlapping rows, and allowed farmers to work longer days despite low visibility and operator fatigue. Productivity gain from variable-rate application came later, once there was enough data to estimate input response from altering the level of each input for each grid cell across the field. Similar issues arise in lower-income, more labor-intensive settings where new machinery might be most valuable for seemingly simple tasks like measuring a field with drones, or using a laser to help level the surface of a field and control runoff.

Integrated Pest Management

Integrated pest management (IPM) is useful as an example of harm reduction rather than eradication. Agricultural pests can include insects, nematodes and mites as well as the pathogens that they transmit such as fungi and bacterial diseases. When pesticides were first developed, many users believed they might be used preventively to bring damage towards zero, in the same way that some human diseases can be mostly or even completely eradicated. High and frequent pesticide application rates that aimed for eradication were thought to be simple and cost-effective, but that led to very high levels of external harm including to the pesticide applicator and other farmers, and also turned out to be less cost-effective than a more management-intensive approach.

IPM starts with monitoring the level and growth of pest populations, and calculating the likely economic impact of the damage they cause. When the economic impact is high enough to justify the full costs—including environmental harms—application is justified. IPM can be seen as an early form of precision agriculture focused on the timing and level of input use, and it predates the development of electronic sensors. Even more information-intensive methods of pest control show considerable promise, including optical and other sensors to detect pathogens, and precision machinery to apply even more limited doses when and where they are needed.

Alternative Proteins and Indoor Agriculture

The practice of growing food indoors is as old as greenhouses, but access to capital for new ventures and the potential availability of low-cost renewable energy has led to many new efforts at growing food under increasingly controlled conditions. Traditional greenhouses give some ability to control temperature, moisture and other aspects of plant growth, but eliminating the soil through hydroponics can be helpful for even more precise control, and then stacking the plants in vertical racks for aeroponics can be helpful to make even more efficient use of energy and light. With both hydroponics and aeroponics the plant is held up on racks instead of its own root system, and nutrients are fed to the plant through water or mist in the air instead of the soil.

Historically the use of indoor farming was limited by the cost of capital and energy to build and operate them. High interest rates on loans for construction and start-up made it difficult to compete with existing farmers' open fields, especially given the relatively low cost and energy efficiency of transporting produce from farms to consumers. For macroeconomic reasons interest rates in the U.S. and other countries fell to zero from 2009 to 2016, offering an exceptionally long period in which many new ventures were funded by private investors seeking unusual opportunities, and the cost of solar and other renewable power sources was falling sharply. Indoor farming for high-value salad greens has been commercially successful in several instances, but even greater investment and interest has flowed into development of alternative proteins that could substitute for the vastly larger quantities of animal source foods.

Alternative protein is a term used broadly for new ways of making meat that replace the animal's metabolism with controlled processes developed through biological engineering. Older plant-based foods with somewhat similar texture and protein or fat content as meat include tofu and tempeh made from soybeans as well as fried foods like falafel. New alternatives developed in the 2000s used more advanced food science to process a plant food like yellow peas plus other ingredients into products that would look, taste and feel more like meat. Plant-based milks had long been made from coconuts and soybeans, but became much more popular when made from oats, almonds and other sources of nutrients, color and taste.

Through the 2010s three new approaches to making meats were of increasing interest: cellular agriculture, precision fermentation and precision photosynthesis. The cellular approach aims to replace the animal by multiplying their cells, feeding the nutrients from plants and protecting them from disease under very controlled conditions. The fermentation approach also uses nutrients from plants, but uses forms of yeast instead of animal cells to create new foods, while precision photosynthesis uses aquatic plants themselves (microalgae). All of these occur inside controlled environments, such as a fully enclosed bioreactor, with the resulting product potentially combined with other ingredients like the original plant-based meats.

Plant-based milks are commercially successful on a large scale, used primarily in coffee or tea and other beverages as well as breakfast cereals. The cost of ingredients and processing is relatively low, especially for oat and soy milk, and their texture or flavor profile is well adapted to beverages and breakfast cereals. Alternative meats may have technological breakthroughs that mimic the texture and flavor of meat, poultry or fish, and also reduce costs sufficiently to make the product attractive, especially if there are low real interest rates and low energy costs to build and operate these facilities.

Urban Agriculture and Community Gardens

Access to agriculture and gardening is a vital aspect of the human experience, and an important amenity for people everywhere. Plots of land reserved for school and community gardens are maintained in cities and towns around the world for that purpose, to ensure that people are able to connect with nature and join together for a common project even if they do not have land of their own. In temperate zones many people use those gardens for seasonal vegetables, and in tropical countries urban people can maintain kitchen gardens much of the year. In some settings, households are actively encouraged to expand them as in the use of Victory Gardens in wartime or when access to food from rural areas is limited for other reasons. In the U.S. and other countries, urban gardens intersect with issues of social justice and community, autonomy and self-reliance as well as use of the produce to promote healthy diets. In many settings the specific foods grown are of great significance, especially for communities that have been displaced and need to maintain continuity with foods of cultural importance to them. Urban gardens can be helpful even for people who do not use them personally, as a green space in the city.

12.1.3 Conclusion

Recent and ongoing changes in how food is grown demonstrate the potential for innovation to transform agricultural production. New production methods allow people to rely less on resources that are increasingly scarce or inputs found to be harmful, and produce healthier foods using inputs that are relatively abundant for those producers.

The shared priority for innovation globally is climate change mitigation and adaptation, building resilience to extreme weather and other climatic shocks. Agriculture plays a major role in that effort, calling for new production methods tailored to needs of each farming region. Agricultural innovation is much more location-specific than innovation for industry and services, not only because of each region's distinctive geography, ecosystems and infrastructure, but also because of differences in the levels and trends in the relative scarcity of different resources.

One of the few near-certainties about the twenty-first century is that the rural population of Sub-Saharan Africa will continue to rise, increasing the number of young workers who have few options other than to be farmers, while the rural populations of all other regions will decline or remain roughly constant and older in age. That difference ensures that young African farmers will be looking for and quickly adopting innovations adapted to a shrinking area of agricultural land per farm household, including higher input use to raise yields. Sustaining support for innovations that meet African farmers' need for intensification, even as governments elsewhere are no longer concerned about shrinking land area per farm in their own countries, is among the many challenges ahead that will shape the future of food.

12.2 Nutrition and Health: Food Environments, Retail Markets and Diet Quality

12.2.1 Motivation and Guiding Questions

Consumers have a strong interest in health for themselves and their loved ones, but the way that each food affects their future health is not usually visible from the food's appearance. Labeling requirements can provide some information, and dietary guidelines by food group can describe what a healthy diet would be, but consumers have many competing influences on their food choices leading to high rates of malnutrition and diet-related disease. Can the future of food be healthier than the past?

The future of groceries for meals at home and food service for meals away from home depends not only on individual choices and food businesses, but also on civic life and activism that influences government policies and programs. In this final section of the book, we address options for shaping the future of food for nutrition for health by returning to our analytical diagrams that distinguish between the roles of income, prices and preferences in food choice. That approach connects the discussion of human behavior in Chapter 8 with the fundamental principles introduced in Chapter 2 and the market failures from Chapters 4–6, providing a rich toolkit to guide intervention towards improved outcomes.

By the end of this chapter, you will be able to:

1. Distinguish among attributes of food and identify promising opportunities to improve diet quality for health and other goals;
2. Define credence goods, and identify attributes of food that are unobservable to consumers and therefore depend on independent quality assurance to be competitively supplied;
3. Describe and give examples of new initiatives and interventions intended to improve nutritional status, using analytical diagrams to predict their impacts; and
4. Compare economics to other ways of approaching agriculture, food and nutrition, including its strengths and limitations from your perspective.

12.2.2 Analytical Tools

An important insight allowing us to understand and potentially improve the food system is to distinguish among the many attributes of each food item and isolate its consequences. Some attributes are immediately visible, prior to purchase, from the outward appearance of an item. Other attributes are noticeable from the taste, smell or texture of a food soon after purchase.

The most basic attribute of a food is its energy content. On average each person on earth consumes just enough energy each day to sustain our body weight and physical activity level, plus enough for child growth and development starting in pregnancy, with some episodes of weight gain when energy intake overshoots those needs. On average our diets change relatively little in terms of total energy per day, but diet composition can vary enormously in ways that impair or improve our future health.

Obstacles to Dietary Change: Trust, Cost and Affordability and Collective Action

A central challenge for the food system is that each food's consequences for future health typically remain unknown even after consumption. These are examples of *credence attributes*, so called because they are a matter of faith. No amount of personal experience will provide convincing evidence about something like whether whole grains are protective against cardiovascular disease. Evidence for that is scientific in nature, coming from biochemistry and clinical studies as well as epidemiological data. Other attributes beyond health are also credence goods, including whether a food is helpful for environmental sustainability, decent work and livelihoods for farmers, or animal welfare. Credibly signaling credence attributes calls for an independent authority to set and enforce a quality standard, which can be voluntary for producers who wish to use that quality certification on their label, or mandatory for all producers in a given product category.

A second challenge for the future of food is access and affordability of foods with desired attributes. Diet cost analysis reveals whether foods with those attributes are not available or have unusually high costs, revealing a lack of access that could be remedied only by improving supply to deliver more of those foods at lower prices. Affordability analysis compares diet costs to a person's income available for food, thereby revealing whether it is even possible for a person with that income level to buy sufficient quantities of even the least expensive locally available items with attributes needed for health. When healthy diets are unaffordable, food choices could potentially improve diet quality but cannot reach international standards without transfer programs that provide additional resources or nutrition assistance. For many people, healthy diets are affordable and yet not chosen, as those items are displaced by other items that are more expensive per day but chosen because they meet needs other than health such as taste and aspirations, or saving time in meal preparation.

A third challenge for the future of food is the difficulty of collective action to remedy market failures and align incentives with the social costs and benefits of each product. Even after analysts have identified opportunities for public action to improve outcomes, it is not easy to interpret public opinion or even voting behavior for willingness to pay for public goods. For example, millions of Americans in California, Massachusetts and elsewhere have voted for referendums that would require all eggs sold in their state to be from hens raised under cage-free conditions. Before the vote they had the option to buy such eggs voluntarily but often did not do so, typically because of the higher cost. This contradiction between voting in a referendum and buying in a store could be a result of uncertainty, if it is not clear the laws would lead to higher egg prices, but can potentially be explained as an understanding of how free ridership affects collective action: these voters might truly be willing to pay more if others also do, but unwilling to take individual action that could be undermined by others' free riding on their choice. As of late 2023, only one-third of U.S. chickens used for egg production are housed in cage-free conditions layers, and it is not clear how animal welfare laws and practices will evolve in the years ahead.

Intervention to Improve Food Choice: The Three Mechanisms Again
In this final section of the book, we return to the basic principles of Section 2.1 that explained how interventions can alter food choices through three distinct mechanisms: price, income or preferences. Prices are influenced by food supply and trade, as part of the food environment that everyone has in common at a given place and time. Income available for food is an individual attribute of each person and their household, from earnings and wealth as well as transfers received. Preferences determine which of the person's affordable items are actually chosen, driven in part by constraints other than money such as time use, and by all the many other factors affecting behavior.

A standard analytical diagram showing interventions that target each of the three mechanisms is shown in Fig. 12.5.

The model used to explain food choice in Fig. 12.5 shows an individual person's consumption of fruits and vegetables on the horizontal axis, and their consumption of all other things projected onto the vertical axis. The diagonal straight lines show all combinations they can afford, with a vertical intercept where they have no fruits and vegetables at all. Food choice among those equally affordable options is explained as the highest attainable level of a indifference curve that is bowed in as shown, leading to the solid round point indicating this person's currently observed choice.

The set of three indifference curves shown by dotted lines below and to the right of the solid round point are drawn to represent this person's long-term best interests, meaning the preferences that their future self wishes they'd had at the time shown in the diagram. For example, a person might eat few fruits

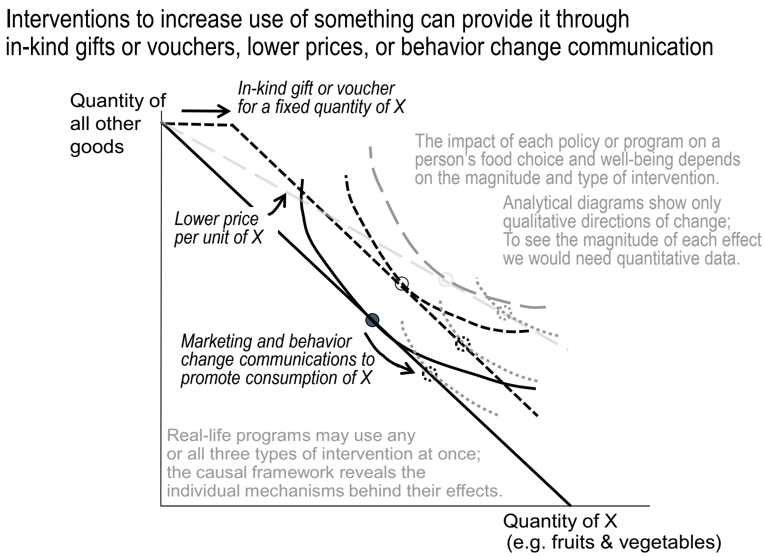

Fig. 12.5 Interventions can alter food choice through three main mechanisms

and vegetables in their 30s and 40s, but come to regret that in their 50s when it turns out that is a risk factor for colorectal cancer.

Intervening to help this person avoid regret—or more precisely, avoid the cancers that would cause regret—could be done purely through marketing and behavior change to alter their preferences. Marketing refers to what private enterprises do to sell their own products, and behavior change refers to public-sector or philanthropic efforts to change peoples' choices. Those marketing and behavior change efforts could focus just on persuasion, as in an advertising campaign, but fruit and vegetable sellers might adopt new more convenient forms of packaging the products, and a public health campaign might try things like teaching people how to cook or even providing them with kitchen equipment.

Efforts at persuasion, such as a behavior change communication campaign with advertisements to eat more vegetables, are generally the least expensive form of intervention per person. Similarly inexpensive interventions to change preferences include changing the placement of things in a store, altering language and imagery with which foods are described, and all of the other marketing activities of companies. Similar efforts to 'nudge' a person's choice in the desired direction might be taken by a school or employer regarding foods in their own cafeteria.

Each food vendor's advertising and marketing efforts, as well as the public and philanthropic efforts at behavior change communication and nudges, work (or don't work) by changing a person's mind about what they want. Altering aspirations in this way is sometimes possible but is difficult, especially given that the marketing and advertising efforts of food companies that influence the observed choice are many times larger in magnitude than any public effort at changing or nudging behavior in a different direction.

A more expensive but often needed intervention is shown with the dark dashed line, whose horizontal segment at the top indicates transfer of a voucher or card that can be used only for fruits and vegetables. In the example drawn, the voucher is for less than the recipient actually wants to consume after receiving the voucher, so they spend some of their own money in addition to the voucher to consume at the dashed circle.

A third kind of intervention that might sometimes be achievable is shown with the light dashed line, indicating a lower price of fruits and vegetables. That could be achieved by removing any policy interventions that raise their price, such as import restrictions or sales taxes on groceries. A lower price might also be achieved by innovation or investments in public infrastructure that lower the cost of production and distribution for competing fruit and vegetable suppliers.

When analysts say they want to 'subsidize' fruits and vegetables, what they usually mean is provide vouchers that cover all or part of the price for a limited quantity which would be drawn like the dark dashed line. The light dashed line refers to the price for everyone, and that cannot be reduced without changing the cost of supply or trade and distribution.

In practice, many interventions combine behavior change communication with a voucher for all or part of a product's price. That combination is a longstanding instrument of marketing, using the voucher to attract and retain attention and the communication to influence how the voucher is perceived and used. When vouchers or transfers are given without behavior change communication, the way they affect choice depends on whether or not the recipient spends some of their own money on the product in addition to the voucher.

Consumer response to a voucher program was discussed in Chapter 8 on food and health behavior, around three different panels in Fig. 8.7. Those concepts are repeated here in the form of a single diagram, as Fig. 12.6.

The choices shown in Fig. 12.6 start at the solid line and curve, and proceed with the dark dashed voucher for fruits and vegetables leading to the open circle. At that point the recipient is spending some of their own money in addition to the voucher. In economics jargon, the voucher is 'infra-marginal' to the person's choice, because the incremental last unit of fruits and vegetables bought by the person is purchased with their own money. This matters because some interventions are designed to be of this type. For example, if we had drawn the diagram with all food purchased at grocery stores along the horizontal axis, the U.S. SNAP benefit would have this type of effect. SNAP benefit cards are recharged once per month with an amount that is designed to supplement the recipient's own spending on food at home, so the recipient uses it until the month's electronic benefit is exhausted and then switch to their own spending. The recipient has no interest in using the benefits

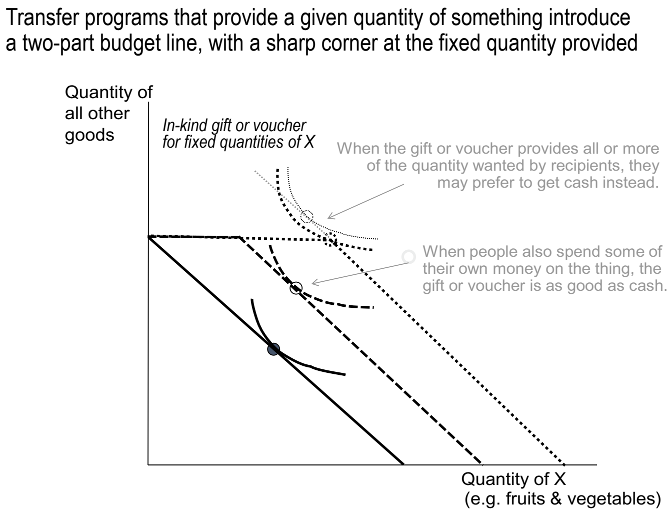

Fig. 12.6 How in-kind gifts or vouchers differ from cash transfers

card for anything other than groceries, because if they did so they would just need to start spending their own money earlier in the month. Keeping the program infra-marginal makes it very likely that recipients will want to use the program funds used as intended, because the voucher is as good as cash for the recipient.

The dotted line shows what would happen if the benefit is large enough that the recipient no longer wants to spend some of their own money on the item in addition to the voucher. Now the voucher is 'extra-marginal' to their spending, as shown by the dark dotted indifference curve, and the recipient could reach a higher indifference curve if they converted some of the benefit to cash and consumed less than the voucher amount of fruits and vegetables. This finding highlights the importance and relevance of accompanying voucher programs with behavior change communications to alter preferences.

12.2.3 Conclusion

This final section of the book is brief because the future of foods for health is up to you. Many different kinds of interventions are used to alter food choice, and all could be informed by the toolkit of economics introduced in this book. People want to be healthy, but choosing foods for health is challenging for at least three fundamental reasons: first of all healthiness is a credence attribute, for which the food's appearance itself conveys little information; then diet cost can be an insurmountable constraint if income available for food is insufficient; and finally each person's preferences, in addition to the prices they pay and the income they have, determine their choices from among affordable options. Those preferences are not easily changed, so interventions typically involve some combination of assistance and persuasion. Rapid changes in the market environment for food both at home and away from home create both the need and the opportunity to anticipate how each person might respond, and how each of us can do our part to form a healthier, more inclusive and sustainable food system.