2. Understanding Food Production

Eating Fossil Fuels

Securing a sufficient quantity and nutritional variety of food is the existential imperative for every species. During their long evolution, our hominin ancestors evolved key physical advantages—erect posture, bipedalism, and relatively large brains—that set them apart from their simian ancestors. This combination of traits enabled them to become better scavengers, collectors of plants, and hunters of small animals.

Early hominins had only the simplest stone tools (hammerstones, choppers), which were useful for butchering animals, but they had no artifacts to aid hunting and catching. They could easily kill injured or sick animals and small, slower-moving mammals, but most of the meat of larger prey came from scavenging kills made by wild predators.[1] The eventual deployment of long spears, shafted axes, bows and arrows, woven nets, baskets, and fishing rods made it possible to hunt and catch a wide variety of species. Some groups—most notably the mammoth hunters of the Upper Paleolithic (this age ended about 12,000 years ago)—mastered the slaughter of large beasts, while many coastal dwellers became accomplished fishers: some even used boats to kill small migrating whales.

The transition from foraging (hunting and collecting) to sedentary living, supported by early agriculture and the domestication of several mammalian and avian species, resulted in a generally more predictable, but still often unreliable, food supply that was able to support much higher population densities than was the case for earlier groups—but this didn't necessarily mean better average nutrition. Foraging in arid environments could require an area of more than 100 square kilometers to support a single family. For today's Londoners, that is roughly the distance from Buckingham Palace to the Isle of Dogs; for New Yorkers, that's how a seagull flies

from Manhattan's tip to the middle of Central Park: a lot of ground to cover simply to survive.

In more productive regions, population densities could rise to as many as 2–3 people per 100 hectares (equal to about 140 standard soccer fields).[2] The only foraging societies with high population densities were coastal groups (most notably in the Pacific Northwest), who had access to annual fish migrations and plentiful opportunities to hunt aquatic mammals: reliable supply of high-protein, high-fat food allowed some of them to switch to sedentary lives in large communal wooden homes, and left them with spare time to carve impressive totem poles. In contrast, early agriculture, where the just-domesticated crops were harvested, meant that more than one person per hectare of cultivated land could be fed.

Unlike the foragers who might have gathered scores of wild species, practitioners of early agriculture had to narrow the variety of the plants they cultivated, as a few staple crops (wheat, barley, rice, corn, legumes, potatoes) dominated typical, overwhelmingly plant-based, diets—but these crops could support population densities that were two or three orders of magnitude higher than in foraging societies. In ancient Egypt, the density rate rose from about 1.3 people per hectare of cultivated land during the predynastic period (pre–3150 BCE) to about 2.5 people per hectare 3,500 years later, when the country was a province of the Roman Empire.[3] This is equivalent to needing an area of 4,000 square meters to feed one person—or almost exactly six tennis courts. But this high production density was (due to the Nile's reliable annual flooding) an exceptionally good performance.

Over time, and very slowly, preindustrial rates of food production rose even higher—but rates of 3 people per hectare were not achieved until the 16th century, and only then in intensively cultivated regions of Ming China; in Europe they remained below 2 people per hectare until the 18th century. This stagnation, or at least very slow gains, in feeding capacity during the long course of preindustrial history meant that until a few generations ago only a small share of well-fed elites did not have to worry about having enough to eat. Even during the occasional years of above-average harvests, typical diets remained monotonous, and malnutrition and undernutrition were common.

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Harvests could fail, and crops were often destroyed in wars—famine was a regular occurrence. As a result, no recent transformation—such as increased personal mobility or a greater range of private possessions—has been so existentially fundamental as our ability to produce, year after year, a surfeit of food. Now most people in affluent and middle-income countries worry about what (and how much) is best to eat in order to maintain or improve their health and extend their longevity, not whether they will have enough to survive.

There are still significant numbers of children, adolescents, and adults who experience food shortages, particularly in the countries of sub-Saharan Africa, but during the past three generations their total has declined from the world's majority to less than 1 in 10 of the world's inhabitants. The United Nations' Food and Agricultural Organization (FAO) estimates that the worldwide share of undernourished people decreased from about 65 percent in 1950 to 25 percent by 1970, and to about 15 percent by the year 2000. Continued improvements (with fluctuations caused by temporary national or regional setbacks due to natural disasters or armed conflicts) lowered the rate to 8.9 percent by 2019—which means that rising food production reduced the malnutrition rate from 2 in 3 people in 1950 to 1 in 11 by 2019.[4]

This impressive achievement is even more noteworthy if expressed in a way that accounts for the intervening large-scale increase of the global population, from about 2.5 billion people in 1950 to 7.7 billion in 2019. The steep reduction in global undernutrition means that in 1950 the world was able to supply adequate food to about 890 million people, but by 2019 that had risen to just over 7 billion: a nearly eightfold increase in absolute terms!

What explains this impressive achievement? Answering that it must be due to higher crop yields is a truism. Saying that the increase has been the combined effect of better crop varieties, agricultural mechanization, fertilization, irrigation, and crop protection correctly describes the changes in key inputs—but it still misses the fundamental explanation. Modern food production, be it field cultivation of crops or the capture of wild marine species, is a peculiar hybrid dependent on two different kinds of energy. The first, and most

obvious, is the Sun. But we also need the now indispensable input of fossil fuels, and the electricity produced and generated by humans.

When asked to give common examples of our reliance on fossil fuels, inhabitants of the colder parts of Europe and North America will think immediately about the natural gas used to heat their houses. People everywhere will point out the combustion of liquid fuels that power most of our transportation but the modern world's most important—and fundamentally existential—dependence on fossil fuels is their direct and indirect use in the production of our food. Direct use includes fuels to power all field machinery (mostly tractors, combines, and other harvesters), the transportation of harvests from fields to storage and processing sites, and irrigation pumps. Indirect use is much broader, taking into account the fuels and electricity used to produce agricultural machinery, fertilizers, and agrochemicals (herbicides, insecticides, fungicides), and other inputs ranging from glass and plastic sheets for greenhouses, to global positioning devices that enable precision farming.

The fundamental energy conversion producing our food has not changed: as always, we are eating, whether directly as plant foods or indirectly as animal foodstuffs, products of photosynthesis—the biosphere's most important energy conversion, powered by solar radiation. What has changed is the intensity of our crop, and animal, production: we could not harvest such abundance, and in such a highly predictable manner, without the still-rising inputs of fossil fuels and electricity. Without these anthropogenic energy subsidies, we could not have supplied 90 percent of humanity with adequate nutrition and we could not have reduced global malnutrition to such a degree, while simultaneously steadily decreasing the amount of time and the area of cropland needed to feed one person.

Agriculture—growing food crops for people and feed for animals—must be energized by solar radiation, specifically by the blue and red parts of the visible spectrum.[5] Chlorophylls and carotenoids, light-sensitive molecules in plant cells, absorb light at these wavelengths and use it to power photosynthesis, a multi-step sequence of chemical reactions that combines atmospheric carbon dioxide and water—as well as small amounts of elements including, notably, nitrogen and phosphorus—to produce new plant mass for grain, legume, tuber, oil, and sugar crops. Part of these harvests is fed to domestic animals to produce meat, milk, and eggs, and additional animal foods come from mammals that graze on grasses and aquatic species whose growth depends ultimately on phytoplankton, the dominant plant mass produced by aquatic photosynthesis.[6]

This has always been so, from the very beginnings of settled cultivation going back some 10 millennia—but two centuries ago the addition of non-solar forms of energy began to affect the crop production and later also the capture of wild marine species. Initially this impact was marginal, and it became notable only in the early decades of the 20th century.

To trace the evolution of this epochal shift, we'll look next at the past two centuries of American wheat production. However, I could quite easily have chosen English or French wheat yields, or Chinese or Japanese rice yields; while agricultural advances may have happened at different times in cultivated parts of North America, Western Europe, and East Asia, there is nothing unique about this comparative sequence that is based on US data.

Three valleys, two centuries apart

We'll start in the Genesee Valley, western New York, in 1801. The new republic is in the 26th year of its existence and yet American farmers grow bread wheat not just the same way their ancestors did before they emigrated from England to British North America a few generations ago, but in a manner not too different from practices in ancient Egypt more than two millennia ago.

The sequence begins with two oxen harnessed to a wooden plow whose cutting edge is shod with an iron plate. Seed, saved from the previous year's crop, is sown by hand, and brush harrows are used to cover it up. Putting the crop in takes about 27 hours of human labor for every seeded hectare.[7] And the most laborious tasks are still to come. The crop is harvested by cutting with sickles; cut stalks are bundled and tied manually in sheaves, and they are stacked upright (to make shocks or stooks) and left to dry. The sheaves are then hauled to a barn and threshed by flailing them on a hard floor, straw is stacked, and grain is winnowed (separated from the chaff), measured, and put into sacks. Securing the crop takes at least 120 hours of human labor per hectare.

The complete production sequence demands about 150 hours of human labor per hectare, as well as about 70 ox-hours. The yield is just one ton of grain per hectare, and of that at least 10 percent has to be set aside as seed for the next year's crop. Altogether, it takes about 10 minutes of human labor to produce a kilogram of wheat, and that would, with wholegrain flour, yield 1.6 kilograms (two loaves) of bread. This is laborious, slow, and low-yielding farming—but it is completely solar, and no other energy inputs are required beyond the Sun's radiation: the crops produce food for people and feed for animals; trees yield wood for cooking and heating; and wood is also used to make metallurgical charcoal for smelting iron ores and producing small metal objects including plow plates, sickles, scythes, knives, and strakes to cover wooden wagon wheels. In modern parlance, we would say that this farming requires no non-renewable (fossil fuel) energy inputs and only a minimum of non-renewable material subsidies (iron components, stones for gristmills), and that the production of both crops and materials relies solely on renewable energies deployed through the exertion of human and animal muscles.

A century later, in 1901, most of the country's wheat comes from the Great Plains and so we move to the Red River Valley, in eastern North Dakota. The Great Plains have been settled and industrialization has made enormous advances during the past two generations—although wheat farming still relies on draft animals, the wheat growing on large Dakota farms is highly mechanized. Teams of four powerful horses pull gang (multi-share) steel plows and harrows, mechanical seed drills are used for planting, mechanical harvesters cut the stalks and bind the sheaves, and only the stooking is done manually. Sheaves are hauled to stacks and fed to threshing machines powered by steam engines, and grain is taken to granaries. The entire sequence takes less than 22 hours per hectare, about 1/7 of the time it did in 1801.[8] In this extensive cultivation, large areas make up for low yields: yields remain low at 1 ton per hectare but the investment of human labor is only about 1.5 minutes per kilogram of grain (compared to 10 minutes in 1801), while the use of draft animals adds up to about 37 horse-hours per hectare, or more than 2 minutes per kilogram of grain.

This is a new, hybrid kind of farming, as the indispensable solar input is augmented by non-renewable anthropogenic energies derived overwhelmingly from coal. The new arrangement requires more animal labor than human labor, and as working horses (and mules in the American South) need grain feed—mainly oats—as well as fresh grass and hay, their large numbers make substantial demands on the country's crop production: about one-quarter of all American farmland is devoted to growing fodder for draft animals.[9]

High-productivity harvests are possible thanks to increasing infusions of fossil energies. Coal is used to make metallurgical coke charged into blast furnaces, and cast iron is converted to steel in open hearth furnaces (see chapter 3). Steel is needed for agricultural machinery as well as for making steam engines, rails, wagons, locomotives, and ships. Coal also powers steam engines and produces the heat and electricity required to manufacture plows, drills, harvesters (also the first combines), wagons, and silos, and to operate railroads and ships that distribute the grain to its final consumers. Inorganic fertilizers are making their first inroads with the imports of Chilean nitrates and with the application of phosphates mined in Florida.

In 2021, Kansas is the country's leading wheat-growing state and so we move to the Arkansas River Valley. In this heart of American wheat country, farms are now commonly three to four times larger than they were a century ago[10]—and yet most of the field work is done by only one or two people operating large machinery. The US Department of Agriculture stopped counting draft animals in 1961, and field work is now dominated by powerful tractors—many models have more than 400 horsepower and eight giant tires—pulling wide implements such as steel plows (with a dozen or more shares), seeders, and fertilizer applicators.[11]

Seed comes from certified growers, and young plants receive optimum amounts of inorganic fertilizers—above all, plenty of nitrogen applied as ammonia or urea—and targeted protection against insects, fungi, and competing weeds. Harvesting, and the concurrent threshing, is done by large combines that transfer grain directly to trucks to be transported to storage silos and sold around the country, or shipped to Asia or Africa. Producing wheat now takes less than two hours of human labor per hectare (compared to 150 hours in 1801), and with yields of around 3.5 tons per hectare this translates to less than two seconds per kilogram of grain.[12]

Many people nowadays admiringly quote the performance gains of modern computing ("so much data") or telecommunication ("so much cheaper")—but what about harvests? In two centuries, the human labor to produce a kilogram of American wheat was reduced from 10 minutes to less than two seconds. This is how our modern world really works. And as mentioned, I could have done similarly stunning reconstructions of falling labor inputs, rising yields, and soaring productivity for Chinese or Indian rice. The time frames would be different but the relative gains would be similar.

Most of the admired and undoubtedly remarkable technical advances that have transformed industries, transportation, communication, and everyday living would have been impossible if more than 80 percent of all people had to remain in the countryside in order to produce their daily bread (the share of the US population who were farmers in 1800 was 83 percent) or their daily bowl of rice (in Japan, close to 90 percent of people lived in villages in 1800). The road to the modern world began with inexpensive steel plows and inorganic fertilizers, and a closer look is needed to explain these indispensable inputs that have made us take a well-fed civilization for granted.

What goes in

Preindustrial farming done with human and animal labor and with simple wooden and iron tools had the Sun as the only source of energy. Today, as ever, no harvests would be possible without Sun-driven photosynthesis, but the high yields produced with minimal labor inputs and hence with unprecedented low costs would be impossible without direct and indirect infusions of fossil energies.

Some of these anthropogenic energy inputs are coming from electricity, which can be generated from coal or natural gas or renewables, but most of them are liquid and gaseous hydrocarbons supplied as machine fuels and raw materials.

Machines consume fossil energies directly as diesel or gasoline for field operations including the pumping of irrigation water from wells, for crop processing and drying, for transporting the harvests within the country by trucks, trains, and barges, and for overseas exports in the holds of large bulk carriers. Indirect energy use in making those machines is far more complex, as fossil fuels and electricity go into making not only the steel, rubber, plastics, glass, and electronics but also assembling these inputs to make tractors, implements, combines, trucks, grain dryers, and silos.[13]

But the energy required to make and to power farm machinery is dwarfed by the energy requirements of producing agrochemicals. Modern farming requires fungicides and insecticides to minimize crop losses, and herbicides to prevent weeds from competing for the available plant nutrients and water. All of these are highly energy-intensive products but they are applied in relatively small quantities (just fractions of a kilogram per hectare).[14] In contrast, fertilizers that supply the three essential plant macronutrients—nitrogen, phosphorus, and potassium—require less energy per unit of the final product but are needed in large quantities to ensure high crop yields.[15]

Potassium is the least costly to produce, as all it takes is potash (KCl) from surface or underground mines. Phosphatic fertilizers begin with the excavation of phosphates, followed by their processing to yield synthetic superphosphate compounds. Ammonia is the starting compound for making all synthetic nitrogenous fertilizers. Every crop of high-yielding wheat and rice, as well as of many vegetables, requires more than 100 (sometimes as much as 200) kilograms of nitrogen per hectare, and these high needs make the synthesis of nitrogenous fertilizers the most important indirect energy input in modern farming.[16]

Nitrogen is needed in such great quantities because it is in every living cell: it is in chlorophyll, whose excitation powers photosynthesis; in the nucleic acids DNA and RNA, which store and process

all genetic information; and in amino acids, which make up all the proteins required for the growth and maintenance of our tissues. The element is abundant—it makes up nearly 80 percent of the atmosphere, organisms live submerged in it—and yet it is a key limiting factor in crop productivity as well as in human growth. This is one of the great paradoxical realities of the biosphere and its explanation is simple: nitrogen exists in the atmosphere as a non-reactive molecule (N_2), and only a few natural processes can split the bond between the two nitrogen atoms and make the element available to form reactive compounds.[17]

Lightning will do it: it produces nitrogen oxides, which dissolve in rain and form nitrates, and then forests, fields, and grasslands get fertilizer from above—but obviously this natural input is too small to produce crop harvests to feed the world's nearly 8 billion people. What lightning can do with tremendous temperatures and pressures, an enzyme (nitrogenase) can do in normal conditions: it is produced by bacteria associated with the roots of leguminous plants (pulses, as well as some trees) or that live freely in soil or in plants. Bacteria attached to the roots of leguminous plants are responsible for most natural nitrogen fixation—that is, for the cleavage of non-reactive N_2 and for the incorporation of nitrogen into ammonia (NH_3), a highly reactive compound that is readily converted into soluble nitrates and can supply plants with their nitrogen needs in return for organic acids synthesized by the plants.

As a result, leguminous food crops, including soybeans, beans, peas, lentils, and peanuts, are able to provide (fix) their own nitrogen supply, as can such leguminous cover crops as alfalfa, clovers, and vetches. But no staple grains, no oil crops (except for soybeans and peanuts), and no tubers can do that. The only way for them to benefit from the nitrogen-fixing abilities of legumes is to rotate them with alfalfa, clovers, or vetches, grow these nitrogen fixers for a few months, and then plow them under so the soils are replenished with reactive nitrogen to be picked up by the succeeding wheat, rice, or potatoes.[18] In traditional agricultures, the only other option to enrich soil nitrogen stores was to collect and apply human and animal wastes. But this is an inherently laborious and inefficient way to supply the nutrient. These wastes have very low nitrogen content and they are subject to volatilization losses (the conversion of liquids to gases—the ammonia smell from manure can be overpowering).

In preindustrial cropping, the wastes had to be collected in villages, towns, and cities, fermented in heaps or pits and—because of their low nitrogen content—applied to fields in massive amounts, commonly 10 tons per hectare but sometimes up to 30 tons (the latter mass being equivalent to 25–30 small European cars), in order to provide the needed nitrogen. Not surprisingly, this was commonly the most time-consuming task in traditional farming, claiming at least a fifth, and as much as a third, of all (human and animal) labor in cropping. Recycling organic wastes is hardly a topic addressed by famous novelists, but Émile Zola, always a complete realist, captured its importance when he described Claude, a young Parisian painter who "had quite a liking for manure." Claude volunteers to toss into the pit "the scourings of markets, the refuse that fell from that colossal table, remained full of life, and returned to the spot where the vegetables had previously sprouted . . . They rose again in fertile crops, and once more went to spread themselves out upon the market square. Paris rotted everything, and returned everything to the soil, which never wearied of repairing the ravages of death."[19]

But at what cost of human toil! This great nitrogen barrier to higher crop yields was nudged only during the 19th century with the mining and export of Chilean nitrates, the first inorganic nitrogenous fertilizer. The barrier was then broken decisively with the invention of ammonia synthesis by Fritz Haber in 1909 and with its rapid commercialization (ammonia was first shipped in 1913), but subsequent production grew slowly and the widespread application of nitrogenous fertilizers had to wait until after the Second World War.[20] New high-yielding varieties of wheat and rice introduced during the 1960s could not express their full yield potential without synthetic nitrogenous fertilizers. And the great productivity shift known as the Green Revolution could not have taken place without this combination of better crops and higher nitrogen applications.[21]

Since the 1970s, the synthesis of nitrogenous fertilizers has undoubtedly been the *primus inter pares* among agricultural energy subsidies—but

the full scale of this dependence is only revealed by looking at detailed accounts of the energy required to produce various common foodstuffs. I have chosen three of them to use as examples, and I picked them because of their nutritional dominance. Bread has been the staple of European civilization for millennia. Given the religious proscriptions on the consumption of pork and beef, chicken is the only universally favored meat. And no other vegetable (although botanically a fruit) surpasses the annual production of tomatoes, now grown not only as a field crop but increasingly in plastic or glass greenhouses.

Each of these foodstuffs has a different nutritional role (bread is eaten for its carbohydrates, chicken for its perfect protein, tomatoes for their vitamin C content) but none of them could be produced so abundantly, so reliably, and so affordably without considerable fossil fuel subsidies. Eventually, our food production will change, but for now, and for the foreseeable future, we cannot feed the world without relying on fossil fuels.

The energy costs of bread, chicken, and tomatoes

Given the enormous variety of breads, I'm going to stick to just a few varieties of leavened breads common in Western diets and now available in places ranging from West Africa (*outre-mer* domain of the French baguette) to Japan (every major department store has a French or German bakery). We have to start with wheat, and helpfully there is no shortage of studies that have attempted to quantify all fuel and electricity inputs and to compare them per harvested area or per unit of yield for different kinds of grain crops.[22] Grain cultivation is at the bottom of the energy subsidy ladder, needing relatively little compared to our other chosen foodstuffs, but as we shall see, it still needs a surprisingly large amount of energy.

Efficient American production of rain-fed wheat on the large fields of the Great Plains requires only about 4 megajoules per kilogram of grain. Because such a large share of this energy is in the form of diesel fuel refined from crude oil, the comparison might be more tangible in terms of equivalents rather than in standard energy units (joules).[23]

Moreover, expressing the needs for diesel fuel in terms of volumes per unit of edible product (be it 1 kilogram, a loaf of bread, or a meal) makes such energy subsidies more readily imaginable.

With diesel fuel containing 36.9 megajoules per liter, the typical energy cost of wheat from the Great Plains is almost exactly 100 milliliters (1 deciliter or 0.1 liters) of diesel fuel per kilogram—just a bit less than half of the US cup measurement.[24] I will use specific volume equivalents of diesel fuel to label individual foodstuffs with the energy embedded in their production.

Basic sourdough bread is the simplest kind of a leavened bread, the staple of European civilization: it contains just bread flour, water, and salt, and the leavening is made, of course, from flour and water. A kilogram of this bread will be about 580 grams of flour, 410 grams of water, and 10 grams of salt.[25] Milling—that is, removing the seed's bran, the outer layer—reduces the mass of milled grains by about 25 percent (a flour extraction rate of 72–76 percent).[26] This means that to get 580 grams of bread flour, we have to start with about 800 grams of whole wheat, whose production requires 80 milliliters of diesel fuel equivalent.

Milling the grain needs an equivalent of about 50 mL/kg to produce white bread flour, while published data for large-scale baking in modern efficient enterprises—consuming natural gas and electricity—indicate fuel equivalents of 100–200 mL/kg.[27] Growing the grain, milling it, and baking a 1-kilogram sourdough loaf thus requires an energy input equivalent of at least 250 milliliters of diesel fuel, a volume slightly larger than the American measuring cup. For a standard baguette (250 grams), the embedded energy equivalent is about 2 tablespoons of diesel fuel; for a large German *Bauernbrot* (2 kilograms), it would be about 2 cups of diesel fuel (less for a wholewheat loaf).

The real fossil energy cost is higher still, because only a small share of bread is now baked where it is bought. Even in France, neighborhood *boulangeries* have been disappearing and baguettes are distributed from large bakeries: energy savings from industrial-scale efficiency are negated by increased transportation costs, and the total cost (from growing and milling grain to baking in a large bakery and distributing bread to distant consumers) may have an equivalent energy consumption as high as 600 mL/kg!

But if the bread's typical (roughly 5:1) ratio of edible mass to the mass of embedded energy (1 kilogram of bread compared to about 210 grams of diesel fuel) seems uncomfortably high, recall that I have already noted that grains—even grains after processing and conversion into our favorite foods—are at the bottom of our food energy subsidy ladder. What would be the consequences of following such a dubious dietary recommendation, now pushed by some promoters under the misleading label of the "Paleolithic diet," as avoiding all cereals and switching instead to diets composed only of meat, fish, vegetables, and fruit?

Rather than tracing the energy cost of beef (a meat that has already been much maligned), I will instead quantify the energy burdens of the most efficiently produced meat—that of broilers reared in large barns in what have become known as CAFOs, central animal feeding operations. In the case of chicken, this means housing and feeding tens of thousands of birds in long rectangular structures where they are crowded in dimly lit spaces (the equivalent of a moonlit night) and fed for about seven weeks before being taken away for slaughter.[28] The US Department of Agriculture publishes statistics on the annual feeding efficiency of domestic animals, and over the past five decades these ratios (units of feed expressed in terms of corn grain per unit of live weight) show no downward trends for either beef or pork, but impressive gains for chicken.[29]

In 1950, 3 units of feed were needed per unit of live broiler weight; now that number is just 1.82, about a third of the rate for pigs and a seventh of the rate for cattle.[30] Obviously, the entire bird (including feathers and bones) is not eaten, and the adjustment for edible weight (about 60 percent of live weight) puts the lowest feed-to-meat ratio at 3:1. Producing one American chicken (whose average edible weight is now almost exactly 1 kilogram) needs 3 kilograms of grain corn.[31] Corn's efficient, rain-fed cultivation has high yields and relatively low energy costs—equivalent to about 50 milliliters of diesel fuel per kilogram of grain—but the energy cost of irrigated corn may be twice as high as that of rain-fed feed, and typical corn yields and feeding efficiencies around the world are lower than in the US. As a result, feed costs alone can be as low as 150 milliliters of diesel fuel per kilogram of edible meat, and as high as 750 mL/kg.

Further energy costs arise from a large-scale intercontinental trade in feedstuffs: it is dominated by the shipment of American corn and soybeans and the sale of Brazilian soybeans. Brazilian soybean cultivation requires the equivalent of 100 milliliters of diesel fuel per kilogram of grain, but trucking the crop from producing areas to ports and shipping it to Europe doubles the energy cost.[32] Growing broilers to slaughter weight also requires energy for heating, air conditioning, and maintaining the poultry houses, for supplying water and sawdust, and for removing and composting waste. These requirements vary widely with location (above all, due to summer air conditioning and winter heating), and hence when combined with the energy cost of delivered feed a wide range of volumes is produced—from 50 to 300 milliliters per kilogram of edible meat.[33]

The most conservative combined rate for feeding and rearing the birds would be thus an equivalent of about 200 milliliters of diesel fuel per kilogram of meat, but the values can go as high as 1 liter. Adding the energy needed for slaughtering and processing the birds (chicken meat is now overwhelmingly marketed as parts, not as whole broilers), retailing, storing and home refrigeration, and eventual cooking raises the total energy requirement for putting a kilogram of roasted chicken on dinner plates to at least 300–350 milliliters of crude oil: a volume equal to almost half a bottle of wine (and for the least efficient producers, to more than a liter).

The minima of 300–350 mL/kg is a remarkably efficient performance compared to the rates of 210–250 mL/kg for bread, and this is reflected in the comparably affordable prices of chicken: in US cities, the average price of a kilogram of white bread is only about 5 percent lower than the average price per kilogram of whole chicken (and wholewheat bread is 35 percent more expensive!), while in France a kilogram of standard whole chicken costs only about 25 percent more than the average price of bread.[34] This helps to explain the rapid rise of chicken to become the dominant meat in all Western countries (globally, pork still leads, thanks to China's enormous demand).

Given that vegans extol eating plants, and that the media have reported extensively on the high environmental cost of meat, you might think that gains in the energy cost of chicken have been surpassed by those in the cultivation and marketing of vegetables. You would be mistaken to think that. The opposite has been true, in fact, and there is no better example to illustrate these surprisingly high energy burdens than taking a close look at tomatoes. They have it all—an attractive color, a variety of shapes, smooth skin, and a juicy interior. Botanically, a tomato is the fruit of the *Lycopersicon esculentum*, a small plant native to Central and South America that was introduced to the rest of the world during the age of first European transatlantic sailings but which took generations to establish worldwide appeal.[35] Eaten out of hand, in soups, filled, baked, chopped, boiled, pureed into sauces, and added to countless salads and cooked dishes, it is now a global favorite embraced in countries ranging from its native Mexico and Peru to Spain, Italy, India, and China (now its largest producer).

Nutritional compendia praise its high vitamin C content: indeed, a large tomato (200 grams) can provide two-thirds of the daily recommended requirement for an adult.[36] But as with all fresh and juicy fruits, it is not eaten for its energy content; it is, overwhelmingly, just an appealingly shaped container of water, which comprises 95 percent of its mass. The remainder is mostly carbohydrate, a bit of protein, and a mere trace of fat.

Tomatoes can be grown anywhere with at least 90 days of warm weather, including the deck of a seaside cottage near Stockholm or in a garden on the Canadian Prairies (in both cases, from plants started indoors). Commercial cultivation is a different matter, however. As with all but a small share of the fruits and vegetables that are consumed in modern societies, tomato cultivation is a highly specialized affair and most of the varieties available in North American and European supermarkets come from only a few places. In the US it is California; in Europe it is Italy and Spain. In order to increase their yield, improve their quality, and reduce the intensity of energy inputs, tomatoes are increasingly grown in plastic-covered single- or multi-tunnel enclosures or in greenhouses—not only in Canada and the Netherlands but also in Mexico, China, Spain, and Italy.

This brings us back to fossil fuels and electricity. Plastics are a less expensive alternative to constructing multi-tunnel glass greenhouses, and the cultivation of tomatoes also requires plastic clips, wedges, and gutter arrangements. Where the plants are grown in the open, plastic sheets are used to cover the soil in order to reduce water evaporation and prevent weeds. The synthesis of plastic compounds relies on hydrocarbons (crude oil and natural gas), both for raw materials (feedstocks) and for the energy needed to produce them. Feedstocks include ethane and other natural gas liquids, and naphtha produced during the refining of crude oil. Natural gas is also used to fuel plastic production, and it is (as already noted) the most important feedstock—the source of hydrogen—for the synthesis of ammonia. Other hydrocarbons serve as feedstocks to produce protective compounds (insecticides and fungicides), because even plants inside glass or plastic greenhouses are not immune to pests and infections.

Expressing the annual operating costs of tomato cultivation in monies is done easily by adding up the expenditure on seedlings, fertilizers, agrochemicals, water, heating, and labor, and by prorating the costs of original structures and devices—metal supports, plastic covers, glass, pipes, troughs, heaters—that are in place for more than one year. But putting a comprehensive energy bill together is not that simple. Direct energy inputs are easy to quantify on the basis of electricity bills and gasoline or diesel fuel purchases, but calculating the indirect flows into the production of materials requires some specialized accounting, and usually some assumptions.

Detailed studies have quantified these inputs and multiplied them by their typical energy costs: for example, the synthesis, formulation, and packaging of 1 kilogram of nitrogenous fertilizer requires an equivalent of nearly 1.5 liters of diesel fuel. Not surprisingly, these studies show a wide range of totals, but one study—perhaps the most meticulous study of tomato cultivation in the heated and unheated multi-tunnel greenhouses of Almería in Spain—concluded that the cumulative energy demand of net production is more than 500 milliliters of diesel fuel (more than two cups) per kilogram for the former (heated) and only 150 mL/kg for the latter harvest.[37]

We get this high energy cost, in large part, because greenhouse

tomatoes are among the world's most heavily fertilized crops: per unit area they receive up to 10 times as much nitrogen (and also phosphorus) as is used to produce grain corn, America's leading field crop.[38] Sulfur, magnesium, and other micronutrients are also used, as are chemicals protecting against insects and fungi. Heating is the most important direct use of energy in greenhouse cultivation: it extends the growing season and improves crop quality but, inevitably, when deployed in colder climates it becomes the single largest user of energy.

Plastic greenhouses located in the southernmost part of Almería province are the world's largest covered area of commercial cultivation of produce: about 40,000 hectares (think of a 20 km × 20 km square) and easily identifiable on satellite images—look for yourself on Google Earth. You can even take a ride on Google Street View, which offers an otherworldly experience of these low-elevation, plastic-covered structures. Under this sea of plastic, the Spanish growers and their local and immigrant African laborers produce annually (in temperatures often surpassing 40°C) nearly 3 million tons of early and out-of-season vegetables (tomatoes, peppers, green beans, zucchini, eggplant, melons) and some fruit, and export about 80 percent of it to EU countries.[39] A truck transporting a 13-ton load of tomatoes from Almería to Stockholm covers 3,745 kilometers and consumes about 1,120 liters of diesel fuel.[40] That works out to nearly 90 milliliters per kilogram of tomatoes, and transport, storage, and packing at the regional distribution centers as well as deliveries to stores raises that to nearly 130 mL/kg.

This means that when bought in a Scandinavian supermarket, tomatoes from Almería's heated plastic greenhouses have a stunningly high embedded production and transportation energy cost. Its total is equivalent to about 650 mL/kg, or more than five tablespoons (each containing 14.8 milliliters) of diesel fuel per medium-sized (125 gram) tomato! You can stage—easily and without any waste—a tabletop demonstration of this fossil fuel subsidy, by slicing a tomato of that size, spreading it out on a plate, and pouring over it 5–6 tablespoons of dark oil (sesame oil replicates the color well). When sufficiently impressed by the fossil fuel burden of this simple food, you can transfer the plate's contents to a bowl, add two or three additional tomatoes, some soy sauce, salt, pepper, and sesame seeds, and enjoy a tasty tomato salad. How many vegans enjoying the salad are aware of its substantial fossil fuel pedigree?

Diesel oil behind seafood

High agricultural productivities of modern societies have made hunting on land (the seasonal shooting of some wild mammals and birds) a marginal source of nutrition in all affluent societies. Wild meat, mostly illegally hunted, is still more common throughout sub-Saharan Africa, but with rapidly growing populations even there it has ceased to be a major source of animal protein. By contrast, marine hunting has never been practiced more widely and more intensively than it is today, as huge fleets of ships—ranging from large modern floating factories to decrepit small boats—scour the world's oceans for wild fish and crustaceans.[41]

As it turns out, capturing what the Italians so poetically call *frutti di mare* is the most energy-intensive process of food provision. Of course, not all seafood is difficult to catch, and harvesting many still-abundant species does not require long expeditions to the remote areas of the southern Pacific. Capturing such plentiful pelagic (living near the surface) species as anchovies and sardines or mackerel can be done with a relatively small energy investment—indirectly in constructing ships and making large nets, directly in the diesel fuel used for ship engines. The best accounts show energy expenditures as low as 100 mL/kg for their capture, an equivalent of less than half a cup of diesel fuel.[42]

If you want to eat wild fish with the lowest-possible fossil carbon footprint, stick to sardines. The mean for all seafood is stunningly high—700 mL/kg (nearly a full wine bottle of diesel fuel)—and the maxima for some wild shrimp and lobsters are, incredibly, more than 10 L/kg (and that includes a great deal of inedible shells!).[43] This means that just two skewers of medium-sized wild shrimp (total weight of 100 grams) may require 0.5–1 liters of diesel fuel to catch—the equivalent of 2–4 cups of fuel.

But, you will object, shrimp are now mostly aquacultured, and haven't these large-scale, industrial-type operations enjoyed the same

advantages that we have exploited so successfully with broilers? Alas, no, because of their fundamental metabolic difference. Broilers are herbivores, and when in confinement their energy expenditure on activity is limited. Therefore feeding them suitable plant matter—now mostly a combination of corn- and soybean-based mixtures—will make them grow fast. Unfortunately, the marine species that people prefer to eat (salmon, sea bass, tuna) are carnivorous, and for their proper growth they need to be fed protein-rich fish meals and fish oil derived from catches of wild species such as anchovies, pilchards, capelin, herring, and mackerel.

Expanding aquaculture—whose total global output, freshwater and marine, is now closing in on the worldwide wild catch (in 2018 it was 82 million tons compared to 96 million tons of wild-caught species)—has eased the pressure on some overfished wild stocks of preferred carnivorous fishes, but it has intensified the exploitation of smaller herbivorous species whose growing harvests are needed to feed expanding aquaculture.[44] As a result, the energy costs of growing Mediterranean sea bass in cages (Greece and Turkey are its leading producers) are commonly equivalent to as much as 2–2.5 liters of diesel fuel per kilogram (a volume about the same as three bottles of wine)—that is, of the same order of magnitude as the energy costs of capturing similarly sized wild species.

As expected, only aquacultured herbivorous fish that grow well consuming plant-based feed—most notably, different species of Chinese carp (bighead, silver, black, and grass carp are the most common)—have a low energy cost, typically less than 300 mL/kg. But, traditional Christmas Eve dinners in Austria, Czech Republic, Germany, and Poland aside, carp is quite an unpopular culinary choice in Europe and it is barely eaten in North America, while demand for tuna, some species of which are now among the most endangered top marine carnivores, has been soaring thanks to the rapid worldwide adoption of sushi.

So, the evidence is inescapable: our food supply—be it staple grains, clucking birds, favorite vegetables, or seafood praised for its nutritious quality—has become increasingly dependent on fossil fuels. This fundamental reality is commonly ignored by those who do not try to understand how our world really works and who are now predicting rapid decarbonization. Those same people would be shocked to know that our present situation cannot be changed easily or rapidly: as we saw in the preceding chapter, the ubiquity and the scale of the dependence are too large for that.

Fuel and food

Several studies have traced the growth of food production's dependence on modern—overwhelmingly fossil—energy inputs, from their absence in the early 19th century to recent rates (ranging from less than 0.25 tons of crude oil per hectare in grain farming to 10 times as much in heated greenhouse cultivation).[45] Perhaps the best way to realize the rise and the extent of this global dependence is to compare the increase of external energy subsidies to the expansion of cultivated land and to the growth of the world's population. Between 1900 and the year 2000, the global population increased less than fourfold (3.7 times to be exact) while farmland grew by about 40 percent, but my calculations show that anthropogenic energy subsidies in agriculture increased 90-fold, led by energy embedded in agrochemicals and in fuels directly consumed by machinery.[46]

I have also calculated the relative global burden of this dependence. Anthropogenic energy inputs into modern field farming (including all transportation), fisheries, and aquaculture add up to only about 4 percent of recent annual global energy use. This may be a surprisingly small share, but it must be remembered that the Sun will always do most of the work of growing food, and that external energy subsidies target those components of the food system where the greatest returns can be expected by reducing or removing natural constraints—be it by fertilizing, irrigating, providing protection against insects, fungi and competing plants, or by promptly harvesting mature crops. The low share may also be seen as yet another convincing example of small inputs having disproportionately large consequences, not an uncommon finding in the behavior of complex systems: think of vitamins and minerals, needed daily in just milligrams (vitamin B6 or copper)

or micrograms (vitamin D, vitamin B12) to keep bodies weighing tens of kilograms in good shape.

But the energy required for food production—field farming, animal husbandry, and seafood—is only a part of the total food-related fuel and electricity needs, and estimating the use in the entire food system results in much higher shares of the total supply. Our best data are available for the US, where, thanks to the prevalence of modern techniques and widespread economies of scale, the direct energy use in food production is now on the order of 1 percent of the total national supply.[47] But after adding the energy requirements of food processing and marketing, packaging, transportation, wholesale and retail services, household food storage and preparation, and away-from-home food and marketing services, the grand total in the US reached nearly 16 percent of the nation's energy supply in 2007 and now it is approaching 20 percent.[48] The factors driving these rising energy needs range from further consolidation of production—and hence growing transportation needs—and growing food import dependency, to more meals eaten away from home and more prepared (convenience) foods consumed at home.[49]

There are many reasons why we should not continue many of today's food-producing practices. Agriculture's major contribution to the generation of greenhouse gases is now the most-often cited justification for following a different path. But modern crop cultivation, animal husbandry, and aquaculture have many other undesirable environmental impacts, ranging from the loss of biodiversity to the creation of dead zones in coastal waters (for more on this see chapter 6)—and there are no good reasons for maintaining our excessive food production with its attendant food waste. So, many changes are clearly desirable, but how fast can they actually happen, and how radically can we reform our current ways in reality?

Can we go back?

Can we reverse at least some of these trends? Can the world of soon-to-be 8 billion people feed itself—while maintaining a variety of crop and animal products and the quality of prevailing diets—without synthetic fertilizers and without other agrochemicals? Could we return to purely organic cropping, relying on recycled organic wastes and natural pest controls, and could we do without engine-powered irrigation and without field machinery by bringing back draft animals? We could, but purely organic farming would require most of us to abandon cities, resettle villages, dismantle central animal feeding operations, and bring all animals back to farms to use them for labor and as sources of manure.

Every day we would have to feed and water our animals, regularly remove their manure, ferment it and then spread it on fields, and tend the herds and flocks on pasture. As seasonal labor demands rose and ebbed, men would guide the plows harnessed to teams of horses; women and children would plant and weed vegetable plots; and everybody would be pitching in during harvest and slaughter time, stooking sheaves of wheat, digging up potatoes, helping to turn freshly slaughtered pigs and geese into food. I do not foresee the organic green online commentariat embracing these options anytime soon. And even if they were willing to empty the cities and embrace organic earthiness, they could still produce only enough food to sustain less than half of today's global population.

The numbers to confirm all of the above are not difficult to marshal. The decline of human labor required to produce American wheat outlined earlier in this chapter is an excellent proxy for the overall impact that mechanization and agrochemicals have had on the size of the country's agricultural labor force. Between 1800 and 2020, we reduced the labor needed to produce a kilogram of grain by more than 98 percent—and we reduced the share of the country's population engaged in agriculture by the same large margin.[50] This provides a useful guide to the profound economic transformations that would have to take place with any retreat of agricultural mechanization and reduction in the use of synthetic agrochemicals.

The greater the reduction of these fossil fuel–based services, the greater the need for the labor force to leave the cities to produce food in the old ways. During the pre-1920 peak of US horse and mule numbers, one-quarter of the country's farmland was dedicated to growing

feed for the more than 25 million American working horses and mules—and at that time US farms had to feed only about 105 million people. Obviously, feeding today's more than 330 million people by deploying "just" 25 million horses would be impossible. And without synthetic fertilizers, yields of food and feed crops dependent on the recycling of organic matter would be a fraction of today's harvest. Corn, America's largest crop, yielded less than 2 tons per hectare in 1920, and 11 tons per hectare in 2020.[51] Millions of additional draft animals would be needed to cultivate virtually all of the country's available farmland, and it would be impossible to find enough recyclable organic matter (and eager Claude-like manure-liking tossers!) or cultivate sufficiently large areas of green manures (rotating grain with alfalfa or clover) to match the nutrients supplied by today's applications of synthetic fertilizers.

This impossibility is best illustrated by a few sets of simple comparisons. Recycling of organic matter is always highly desirable, as it improves the structure of soil, increases its organic content, and provides energy for myriad soil microbes and invertebrates. But the very low nitrogen content of organic matter means that farmers have to apply very large quantities of straw or manure in order to supply enough of this essential plant nutrient to produce high crop yields. The nitrogen content of cereal straws (the most abundant crop residue) is always low, usually 0.3–0.6 percent; manure mixed with animal bedding (usually straw) contains only 0.4–0.6 percent; fermented human waste (China's so-called night soil) has just 1–3 percent; and manures applied to fields rarely contain more than 4 percent.

In contrast, urea, now the world's dominant solid nitrogenous fertilizer, contains 46 percent nitrogen, ammonium nitrate has 33 percent, and commonly used liquid solutions contain 28–32 percent, at least an order of magnitude more nitrogen-dense than recyclable wastes.[52] This means that to supply the same amount of the nutrient to growing crops, a farmer would have to apply anywhere between 10 and 40 times as much manure by mass—and in reality even more of it would be needed, as significant shares of nitrogenous compounds are lost due to volatilization, or dissolved in water and carried below the root level, with the aggregate losses of nitrogen from organic matter being almost always higher than those from a synthetic liquid or solid.

Moreover, there would be a more than commensurate claim on labor, as the handling, transporting, and spreading of manure is far more difficult than dealing with small, free-flowing granules that can be easily applied by mechanical spreaders or (as is done with urea in small Asian rice fields) simply by sowing it by hand. And regardless of the effort that might be put into organic recycling, the total mass of recyclable materials is simply too small to provide the nitrogen required by today's harvests.

Global inventory of reactive nitrogen shows that six major flows bring the element to the world's croplands: atmospheric deposition, irrigation water, plowing-under of crop residues, spreading of animal manures, nitrogen left in soil by leguminous crops, and application of synthetic fertilizers.[53]

Atmospheric deposition—mainly as rain and snow containing dissolved nitrates—and recycled crop residues (straws and plant stalks that are not removed from fields to feed animals or burned onsite) each contribute about 20 megatons of nitrogen per year. Animal manures applied to fields, mainly from cattle, pigs, and chickens, contain almost 30 megatons; a similar total is introduced by leguminous crops (green manure cover crops, as well as soybeans, beans, peas, and chickpeas); and irrigation water brings about 5 megatons—for a total of about 105 megatons of nitrogen per year. Synthetic fertilizers supply 110 megatons of nitrogen per year, or slightly more than half of the 210–220 megatons used in total. This means that at least half of recent global crop harvests have been produced thanks to the application of synthetic nitrogenous compounds, and without them it would be impossible to produce the prevailing diets for even half of today's nearly 8 billion people. While we could reduce our dependence on synthetic ammonia by eating less meat and wasting less food, replacing the global input of about 110 megatons of nitrogen in synthetic compounds by organic sources could be done only in theory.

Multiple constraints limit the recycling of manure produced by

animals in confinement.[54] In traditional mixed farming, cattle, pig, and poultry manure from relatively small numbers of animals was directly recycled on adjacent fields. Producing meat and eggs in central animal feeding operations reduced this option: these enterprises generate such large quantities of waste that its application to fields would overload soils with nutrients within the radius where it would be profitable to spread it; presence of heavy metals and drug residues (from feed additives) is another problem.[55] Similar constraints apply to the expanded use of sewage sludge (biosolids) from modern human waste treatment plants. Waste's pathogens must be destroyed by fermentation and by high-heat sterilization, but such treatments do not kill all antibiotic-resistant bacteria and do not remove all heavy metals.

Grazing animals produce three times as much manure as do mammals and birds kept in confinement: the FAO estimates that they leave annually about 90 megatons of nitrogen in waste—but exploiting this large source is impractical.[56] Accessibility would limit any gathering of animal urine and excrement to a fraction of the hundreds of millions of hectares of pastures where these wastes are expelled by grazing cattle, sheep, and goats. Gathering it would be as prohibitively costly as its transportation to treatment points and then to crop fields. Moreover, intervening nitrogen losses would further reduce the already very low nitrogen content of such wastes before the nutrient could reach the fields.[57]

Another choice is to expand the cultivation of leguminous crops to produce 50–60 megatons of nitrogen per year, rather than about 30 megatons as they currently do—but only at a considerable opportunity cost. Planting more leguminous cover crops such as alfalfa and clover would boost nitrogen supply but would also reduce the ability to use one field to produce two crops in a year, a vital option for the still-expanding populations of low-income countries.[58] Growing more leguminous grains (beans, lentils, peas) would lower the overall food energy yields, because they yield far less than cereal crops and, obviously, this would reduce the number of people that could be supported by a unit of cultivated land.[59] Moreover, the nitrogen left behind by a soybean crop—commonly 40–50 kilograms of nitrogen per hectare—would be less than the typical American applications of nitrogenous fertilizers, which are now about 75 kg N/ha for wheat and 150 kg N/ha for grain corn.

Another obvious drawback of expanded rotations with leguminous crops is that in colder climates, where only a single crop can be grown in a year, cultivation of alfalfa or clover would preclude the annual planting of a food crop, while in warmer regions with double-cropping it would reduce the frequency of harvesting food crops.[60] While it might be possible in countries with small populations and plentiful farmland, it would, inevitably, reduce food-producing capacity in all places where double-cropping is common, including large parts of Europe and the North China Plain, the region that produces about half of China's grain.

Double-cropping is now practiced on more than a third of China's cultivated land, and more than a third of all rice comes from double-cropping in South China.[61] Consequently, the country would find it impossible to feed its now more than 1.4 billion people without this intensive cultivation that also requires record-level nitrogen applications. Even in traditional Chinese farming, famous for its high rate of organic recycling and for complex crop rotations, farmers in the most intensively cultivated regions could not supply more than 120–150 kg N/ha—and doing so required extraordinarily high labor inputs, with (as already stressed) manure collection and application being the most time-consuming.

Even so, such farms could produce only overwhelmingly vegetarian diets for 10–11 people per hectare. In contrast, China's most productive double-cropping depends on applications of synthetic nitrogenous fertilizers averaging more than 400 kg N/ha, and it can produce enough to feed 20–22 people whose diets contain about 40 percent animal and 60 percent plant protein.[62] Global crop cultivation supported solely by the laborious recycling of organic wastes and by more common rotations is conceivable for a global population of 3 billion people consuming largely plant-based diets, but not for nearly 8 billion people on mixed diets: recall that synthetic fertilizers now supply more than twice as much nitrogen as all recycled crop residues and manures (and given the higher losses from organic applications, the effective multiple is actually closer to three!).

Doing with less—and doing without

But none of this means that major shifts in our dependence on fossil fuel subsidies in food production are impossible. Most obviously, we could reduce our crop and animal production—and the attendant energy subsidies—if we wasted less food. In many low-income countries, poor crop storage (making grains and tubers vulnerable to rodents, insects, and fungi) and the absence of refrigeration (accelerating the spoilage of dairy products, fish, and meat) wastes too much food even before it reaches its markets. And in affluent countries, food chains are longer and opportunities for inadvertent food losses arise at every step.

Even so, the well-documented global food losses have been excessively high, mostly because of an indefensible difference between output and actual needs: daily average per capita requirements of adults in largely sedentary affluent populations are no more than 2,000–2,100 kilocalories, far below the actual supplies of 3,200–4,000 kilocalories.[63] According to the FAO, the world loses almost half of all root crops, fruits, and vegetables, about a third of all fish, 30 percent of cereals, and a fifth of all oilseeds, meat, and dairy products—or at least one-third of the overall food supply.[64] And the UK's Waste and Resources Action Programme ascertained that inedible household food waste (including fruit and vegetable peelings, and bones) is only 30 percent of the total, meaning that 70 percent of wasted food was perfectly edible and was not consumed either because it spoiled or because too much of it was served.[65] Reducing food waste might seem to be much easier than reforming complex production processes, and yet this proverbial low-hanging fruit has been difficult to harvest.

Eliminating waste that takes place all along the long and complex production-processing-distribution-wholesaling-retailing-consumption chain (from fields and barns to plates) is extremely challenging. American food balances show that the nationwide share of wasted food has remained stable during the past 40 years, despite perennial calls for improvements.[66] And higher food waste accompanied China's improving nutrition as the country moved from the precarious food supply that prevailed until the early 1980s to averaging per capita rates that are now higher than in Japan.[67]

Higher food prices should lead to lower waste, but this is not a desirable way to fix the problem in low-income countries—where food access for many disadvantaged families remains precarious and where food still claims a large share of overall family spending—while in affluent nations, where food is relatively inexpensive, this would require substantial price hikes, a policy that has no eager promoters.[68]

In well-off societies, a better way to reduce agriculture's dependence on fossil fuel subsidies is to make appeals for adopting healthy and satisfactory alternatives to today's excessively rich and meaty diets—the easiest choices being moderate meat consumption, and favoring meat that can be grown with lower environmental impact. The quest for mass-scale veganism is doomed to fail. Eating meat has been as significant a component of our evolutionary heritage as our large brains (which evolved partly because of meat eating), bipedalism, and symbolic language.[69] All our hominin ancestors were omnivorous, as are both species of chimpanzees (*Pan troglodytes* and *Pan paniscus*), the hominins closest to us in their genetic makeup; they supplement their plant diet by hunting (and sharing) small monkeys, wild pigs, and tortoises.[70]

Full expression of human growth potential on a population basis can take place only when diets in childhood and adolescence contain sufficient quantities of animal protein, first in milk and later in other dairy products, eggs, and meat: rising post-1950 body heights in Japan, South Korea, and China, as a result of increased intake of animal products, are unmistakable testimonies to this reality.[71] Conversely, most people who become vegetarians or vegans do not remain so for the remainder of their lives. The idea that billions of humans—across the world, not only in affluent Western cities—would willfully not eat any animal products, or that there'd be enough support for governments to enforce that anytime soon, is ridiculous.

But none of this means that we could not eat much *less* meat than affluent countries have averaged during the past two generations.[72] When expressed in terms of carcass weight, annual meat supply in many high-income countries has averaged close to, or even in excess of, 100 kilograms per capita—but the best nutritional advice is that we do not have to eat more than an adult's body mass equivalent in meat per year to obtain an adequate amount of high-quality protein.[73]

While veganism is a waste of valuable biomass (only ruminants—that is cattle, sheep, and goats—can digest such cellulosic plant tissues as straw and stalks), high-level carnivory has no proven nutritional benefits: it certainly does not add any years to life expectancy, and it is a source of additional environmental stress. Meat consumption in Japan, the country with the world's highest longevity, has recently been below 30 kilograms per year; and a much less appreciated fact is that similarly low consumption rates have become fairly common in France, traditionally a nation of high meat intake. By 2013, nearly 40 percent of adult French were *petits consommateurs*, eating meat only in small amounts adding up to less than 39 kg/year, while the heavy meat consumers, averaging about 80 kg/year, made up less than 30 percent of French adults.[74]

Obviously, if all high-income countries were to follow these examples, they could reduce their crop harvests—because most of their grain harvests are not destined directly for food but for animal feed.[75] But this is not a universal option. While meat intakes in many affluent countries have been declining and could be cut even further, they have been rising rapidly in such modernizing nations as Brazil and Indonesia (where they have more than doubled since 1980) and China (where they have quadrupled since 1980).[76] Moreover, there are billions of people in Asia and Africa whose meat consumption remains minimal and whose health would benefit from more meaty diets.

Additional opportunities to reduce the dependence on synthetic nitrogenous fertilizers come on the production side—for example, improving the efficiency of nitrogen uptake by plants. But again, these opportunities are circumscribed. Between 1961 and 1980 there was a substantial decline in the share of applied nitrogen actually incorporated by crops (from 68 percent to 45 percent), then came a levelling off at around 47 percent.[77] And in China, the world's largest consumer of nitrogen fertilizer, only a third of the applied nitrogen is actually used by rice; the rest is lost to the atmosphere and to ground and stream waters.[78] Given that we are expecting at least 2 billion more people by 2050, and that more than twice as many people in the low-income countries of Asia and Africa should see further gains—both in quantity and quality—in their food supply, there is no near-term prospect for substantially reducing the global dependence on synthetic nitrogenous fertilizers.

There are obvious opportunities for running field machinery without fossil fuels. Decarbonized irrigation could become common with pumps powered by solar- or wind-generated electricity rather than by combustion engines. Batteries with improving energy density and lower cost would make it possible to convert more tractors and trucks to electric drive.[79] And in the next chapter I will explain the alternatives to the dominant, natural gas–based synthesis of ammonia. But none of these options can be adopted either rapidly or without additional (and often substantial) investments.

These advances are, at present, a very long way off. They will depend on inexpensive renewable electricity generation backed up by adequate large-scale storage, a combination that is yet to be commercialized (and an alternative to large pumped hydro storage is yet to be invented; for more see chapter 3). A nearly perfect solution would be to develop grain or oil crops with the capabilities common to leguminous plants—that is, with their roots hosting bacteria able to convert inert atmospheric nitrogen to nitrates. Plant scientists have been dreaming about this for decades, but no releases of commercial nitrogen-fixing varieties of wheat or rice are coming anytime soon.[80] Nor is it very likely that all affluent countries and better-off modernizing economies will adopt large-scale voluntary reductions in the quantity and variety of their typical diets, or that the resources (fuel, fertilizers, and machinery) saved by such pullbacks would be transferred to Africa to improve the continent's still-dismal nutrition.

Half a century ago, Howard Odum—in his systematic examination of energy and the environment—noted that modern societies "did not understand the energetics involved and the various means by which the energies entering a complex system are fed back as subsidies indirectly into all parts of the network . . . industrial man no longer eats potatoes made from solar energy; now he eats potatoes partly made of oil."[81]

Fifty years later, this existential dependence is still insufficiently appreciated—but the readers of this book now understand that our food is partly made not just of oil, but also of coal that was used to produce the coke required for smelting the iron needed for field, transportation, and food processing machinery; of natural gas that serves as both feedstock and fuel for the synthesis of nitrogenous fertilizers; and of the electricity generated by the combustion of fossil fuels that is indispensable for crop processing, taking care of animals, and food and feed storage and preparation.

Modern agriculture's higher yields are not produced with a fraction of the labor that was required just a lifetime ago because we have improved the efficiency of photosynthesis, but because we have provided better varieties of crops with better conditions for their growth by supplying them with adequate nutrients and water, by reducing weeds that compete for the same inputs, and by protecting them against pests. Concurrently, our much-increased capture of wild aquatic species has depended on expanding the extent and the intensity of fishing, and the rise of aquaculture could not happen without providing requisite enclosures and high-quality feed.

All these critical interventions have demanded substantial—and rising—inputs of fossil fuels; and even if we try to change the global food system as fast as is realistically conceivable, we will be eating transformed fossil fuels, be it as loaves of bread or as fishes, for decades to come.